# On the Similarity of Electric Field Signatures of Upward and Downward Negative Leaders

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***Abstract*—We report on general characteristics of simultaneous channel-base current and distant electric fields for five upward positive flashes recorded at the Säntis tower in Summer 2014. We describe the salient features of the upward negative leader process initiating upward positive flashes and compare them with those of the downward negative leader process found in the literature. Our observations show considerable similarity between those two processes.**

***Keywords- Upward Positive Flash; Upward Negative Leader; Downward Negative Leader; Electric Field.***

## I. INTRODUCTION

Upward positive flashes are initiated by negative upward leaders from the top of elevated structures [1], [2] and they may involve return-stroke-type processes. This kind of flash is less frequent compared to other lightning activity and, as a result, knowledge of upward positive flashes is limited to a few studies (e.g. [1]–[4]).

Upward positive flashes have been classified into two types based on features of their channel-base current, one of the criteria being that type 1 flashes exhibit a main unipolar pulse that is absent in type 2 flashes [3].

A classification of upward flashes was introduced by Wang et al. [5] based on the presence or absence of other lightning activity in the geographical and temporal vicinity of upward flashes. Based on Wang et al.'s classification, Heidler et al. proposed a similar classification of upward positive flashes based on the preceding lightning activity into self-triggered and other-triggered events [6].

At present, the only high-speed video observations along with channel-base current records of natural upward positive flashes have been presented by Miki et al [4]. Miki et al. reported on negative upward stepped luminosity pulses during the course of a flash with longer average leader lengths than for negative downward leaders reported in the literature by Hill et al. [7] (some tens of meters compared to some meters), although according to Schonland [8], the typical step length in downward negative leaders is about 50 m and the lengths can be as high as 200 m. Miki et al. stated that limited space resolution of their camera may have caused an overestimation of the leader step length and also this issue could prevent different phases of the stepping process from being resolved in the video observations.

More recently, Pu et al. [9] reported, for the first time, on simultaneous measurements of the lightning channel-base current, close-range magnetic fields, and high-speed video recordings for upward positive triggered-lightning. However, the stepping process could not be resolved in their optical observations due to a limited frame rate. In fact, the stepping process occurs on a sub-microsecond scale. The only optical study approaching such time resolution is that of Gamerota et al. in 2014 [10].

On the other hand, numerous studies have been conducted to characterize the formation and progression of downward negative leaders (e.g. [11]–[16]). However, direct measurements of the associated current waveforms, not directly measurable, at least at present, are unavailable [17], [18].

The initiation mechanism of lightning is one of the most important unanswered questions and recent studies have cast doubt on the involvement of the Relativistic Runaway Electron Avalanche [19], which is currently one of the initiation mechanism theories.

To the best of authors' knowledge, the differences and similarities between initiation, formation and progression of upward and downward negative lightning leaders have not been established yet.

In this study, we present and compare electric field signatures of upward negative leaders from lightning to the Säntis tower and compare them with observations on downward negative leader processes available in the literature.

This paper is organized as follows: Section II briefly presents the instrumentation at the Säntis tower and at the electric field measuring station. Section III presents the obtained data and an analysis on the signatures of upward negative leader processes. A discussion and qualitative comparison of the downward and upward negative leader processes is given in section IV. Finally, conclusions are given in Section V.

## II. Instrumentation

### A. Current Measurement System

The Säntis Tower was instrumented in May 2010 to record lightning channel-base current waveforms striking the tower. The current waveform and its derivative are measured at two heights of 24 and 82 m from the tower base using Rogowski coils and multi-gap B-dot sensors. More information on the Säntis Tower current measurement system can be found in [20].

### B. Electric Field Measurement Station

A station for measuring wideband electric fields associated with flashes striking the Säntis tower was deployed on July 23, 2014 and was operational until 28 October, 2014. The operating frequency bandwidth of the system is 2 kHz to 150 MHz. A PCI-5122 digitizer with a sampling rate of 50 MS/s was used to digitize and record field waveforms. The electric field sensor was installed on the roof of a 25-m tall building (Huber+Suhner) in Herisau, 14.7 km away from the Säntis Tower. More information on the installed electric field system can be found in [21].

## III. Current and Field Signatures of Upward Negative Leaders

In this section, we present an analysis of simultaneous channel-base current and electric field records of five type-2 upward positive flashes that were obtained during the summer measurement campaign of 2014 [3].

It should be noted that during this observation period, no GPS timestamps were available and the current and field waveforms were synchronized using the patterns of inter-pulse intervals of pulse sequences. Figure 1 shows an example of current and electric field records of our dataset which occurred on October 21, 2014 at 23:56:46, in which a negative sign is used for current waveforms associated with positive flashes and the physics sign convention is used to represent the electric field waveform. We will use these same conventions for fields and currents unless otherwise specified in the figure caption.

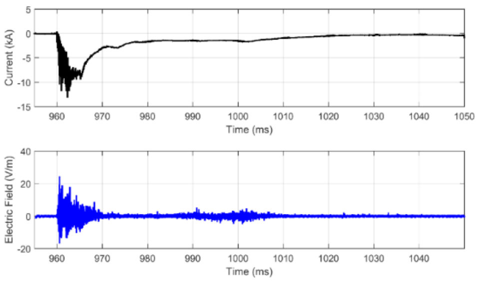


Figure 1. Current (top) and E-field (bottom) waveforms associated with a type-2 upward positive flash that occurred on 21th October 2014, 23:56:46 (local time).

In the following subsections, we present and discuss individual and overall waveform characteristics of upward negative leader pulses.

### A. Observed Characteristics of Individual Pulses

Herein, we investigate features of individual pulses recorded during the course of the upward negative leader such as the one whose overall waveform is presented in Figure 1.

Close inspection of the recorded current and field waveforms of the upward negative leader process reveals that individual pulses can be classified into two major categories:

Category A Pulses: Pulses with a bipolar E-field signature that start with a positive initial half-cycle, which usually can be correlated with a negative unipolar current pulse. This first category of observed pulses is illustrated in Figure 2, in which the current and E-field pulses can be clearly correlated. The electric field pulse shows a bipolar behavior with an initial excursion of positive polarity and an overall duration of about 23 µs. For future reference in this paper, we label this type of pulses "Category A". More details on the characteristics of Category A pulses can be found in [21].

Category B Pulses: Mainly unipolar positive or negative E-field pulses which are not correlated with any major current pulse. Figures 3 and 4 show examples of electric field pulses of the second category. These E-field pulses are characterized by a much smaller width than Category A pulses (some microseconds for Category B compared to some tens of microseconds for Category A) and they can be either unipolar (of either polarity) or bipolar.

As shown in Figure 5, Category B pulses may occur simultaneously with Category A pulses. The presence of two distinct types of pulses makes the pulse width distribution for Category A and B pulses be bimodal, as reported in [14]).

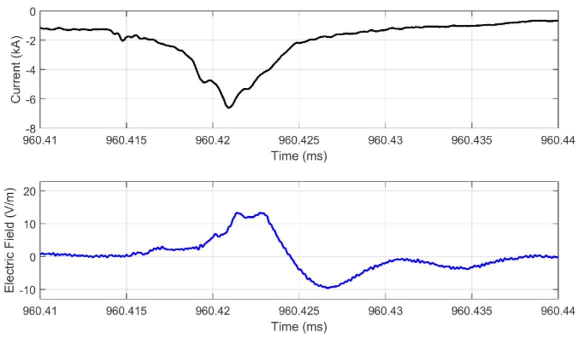


Figure 2. The first category of observed pulses (Category A pulse). Current (top) and electric field (bottom). The overall flash waveforms are shown in Figure 1.

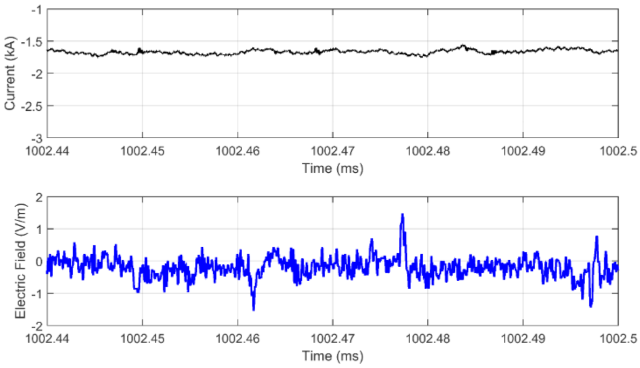


Figure 3. Examples of unipolar electric field pulses belonging to Category B without any associated major current pulse. Current (top). Electric field (bottom). The overall waveform of the flash is shown in Figure 1.

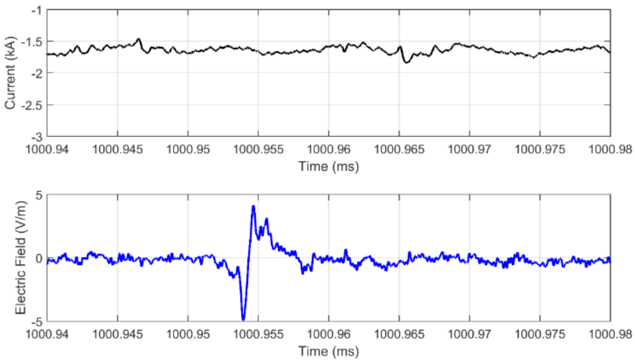


Figure 4. An example of a bipolar electric field pulse of Category B without any major current pulse. Current (top). Electric field (bottom). The overall waveform of the flash is shown in Figure 1.

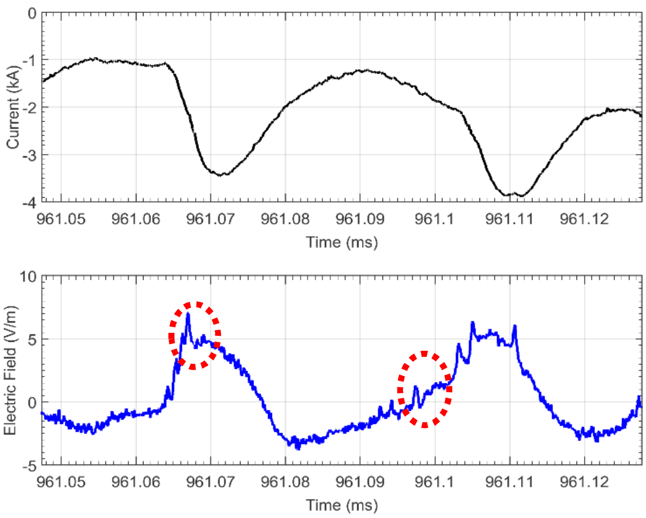


Figure 5. Category B pulses (enclosed by red dashed-line ellipses) Superimposed on Category A pulses (leading to a bimodal pulse width distribution of Category A and B pulses [14]).

## *B. Overall Waveform Characteristics*

As it can be observed in Figure 1, the current signature is characterized by a millisecond-scale waveform with large, oscillatory pulse trains superimposed on its rising portion, typical of type-2 flashes [3], while the electric field waveform is characterized by two distinct periods of pulsations separated by a no-pulse time-interval between them. Expanded views of the first pulsation period are shown in Figure 6 and Figure 7. This stage contains generally Category A pulses, which might have some superimposed Category B pulses. The characteristics of the pulses evolve with time. We can observe that as time advances:

- Category A pulses become slower (the risetime and width of pulses increase, see Fig. 6 and Figure. 7)
- The correlation between current and field for Category A pulses decreases (the current pulses tend to vanish while the field pulses are still discernible, see Figure. 7).
- Current pulses of Category A become less significant in amplitude and, as a result, they radiate less (Figure. 7).
- As the fields due to Category A pulses vanish, Category B pulses start to dominate (Figure. 7).

As can be seen from Fig. 1, during the time period from about 970 to about 980 ms, the current is characterized by a slow, millisecond-scale waveform and the associated field is nearly equal to zero. Neither the current nor the field present any pulses in this (second) stage.

During the time period from about 980 to 1010 ms (see Figure. 1), the field is characterized by fast chaotic bipolar and unipolar pulses of Category B. No current pulses can be observed in this (third) stage.

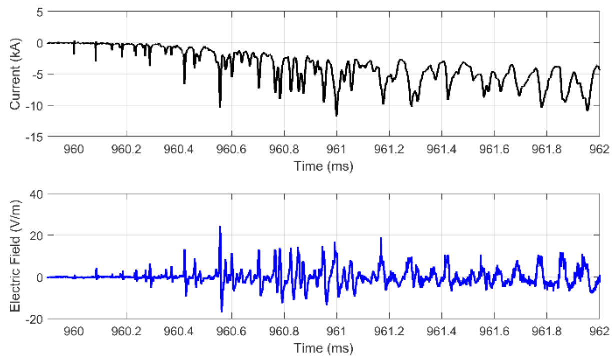


Figure 6. Expanded view of the rising portion (first stage) of the current (top) and E-field (bottom) waveforms of the flash presented in Figure 1.

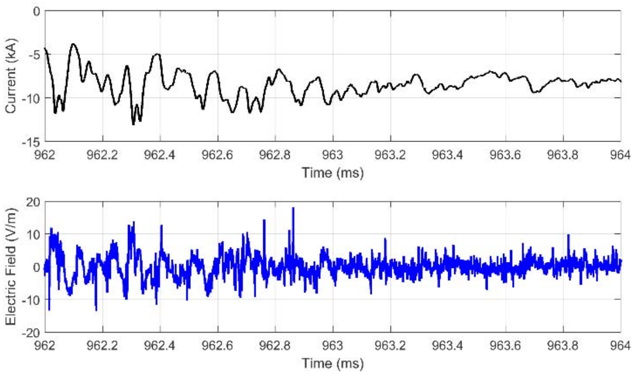


Figure 7. Continuation of field and current of Figure 6.

It is worth noting that all recorded upward positive flashes in our dataset include the three stages described above. In some cases, pulses associated with the third stage (Category B field pulses with no correlated current pulses) can be seen repeatedly, accompanied with no-pulse intervals in between them. We hypothesize that these might be due to the branching of the upward negative leader.

## IV. Discussion on the Similarity of Upward and Downward Negative Leader Process

Numerous studies have been conducted to investigate the initiation process of downward negative flashes using various means including electric field observations, VHF mapping, and optical observations (e.g. [11], [12], [15]).

Clarence and Malan proposed a three-phase mechanism including Breakdown, Intermediate, and Leader (BIL) prior to the first return stroke of a downward flash [11] and they hypothesized that the initial breakdown (Stage B) process must be entirely different from the stepped leader process (Stage L). Other studies based on VHF observations suggested that similar discharge processes occur in stages B and L [12].

The difference in the underlying physical mechanisms of the B and L processes, and the reason behind the presence of stage I is an ongoing debate. Examples of overall field waveforms and individual pulses associated with the BIL phases can be found in ([14], [15], [22], [23]).

Two types of electric field pulsations were reported by Nag et al. [24] to occur during the B and L stages, which they called "Classical" and "Narrow" preliminary breakdown pulses, respectively. Examples of these types of pulses are shown in Figure 8.

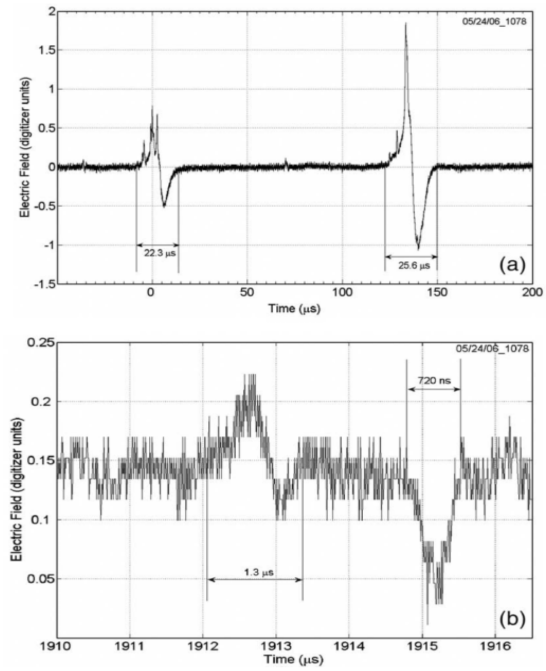


Figure 8. Examples of (a) Classical and (b) Narrow PBPs in a downward negative flash (Adapted from [[24]]). The atmospheric sign convention is used in this figure.

Recently, Stolzenberg et al. [13], using a high speed video camera, introduced the concept of "initial leader" for initial breakdown pulses (in stage B), which differs from normal stepped leaders (in stage L). They suggested that the initial leader process can be characterized by the following successive steps:

- A dim linear feature moves downward from the initiation point (a slow decrease in the E-change).
- An impulsive breakdown at the lower end of the initial leader.
- An upward-moving brightness.

They hypothesized that the initial leader pulses stop to occur because the previous initial leaders moved enough charge to reduce the ambient electric field near the initiation point.

On the other hand, Campos and Saba observed that the channel extension in stage B is quite similar to the ordinary leader extension observed in stage L [15].

More recently, Petersen and Beasley [14] observed a bimodal distribution of step lengths (and field pulse widths) in the stepping process, involving both long (i.e., 200+ m length) and short (i.e., 10+ m length) steps. Figure 9 shows examples of pulses in the B and L stages. The same kind of pulsation observed in stage L (So-Called "Narrow PBP") was observed in stage B, superimposed on less fast pulses (So-called "Classical PBP").

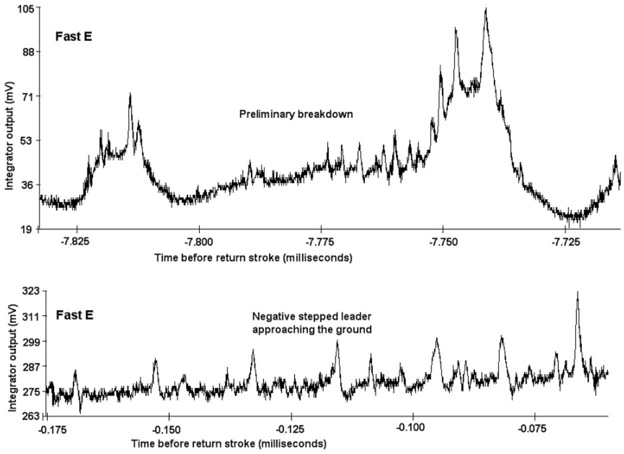


Figure 9. Electric field pulses recorded during stage B (top), and during stage L (bottom). The atmospheric sign convention is used in this figure. Adapted from [14].

They suggested the presence of distant space leaders with their negative ends stepping downward and generating narrow pulses (like those in stage L), while their positive ends generate classical pulses when they attach to the previously formed leader channel in the former similar steps (major pulses in Stage B). When the ambient electric field is reduced by the descent of the leader, less distant space leaders occur, which eventually leads to the generation of narrow pulses only.

Figures 1 to 7 present the typical overall and individual pulse behavior of upward negative leaders observed in our study. As seen in Figure 1, similar to the downward negative leader process, a breakdown stage, an intermediate stage, and a leader stage can be identified in our field record. In addition, comparison of the observed individual pulses in the upward negative leader process (e.g. Figures 2-5) with those of Classical PBPs, Narrow PBPs and the bimodal distribution of pulse widths in the downward negative leader process strengthens the hypothesized similarity of the upward and downward leader processes.

A quantitate study of the Category A pulses of our dataset was reported in [21]. Table 1 presents the average and standard deviations of some parameters of the electric field waveforms of Category A pulses. The obtained average pulse width of 25.7 μs is in agreement with former studies on Classical PBPs, reported to be in the range of 20 to 40 μs [25].

TABLE I. STATISTICS OF CHARACTERISTICS OF THE FIRST CATEGORY ELECTRIC FIELD PULSES (CATEGORY A). PEAK VALUES ARE NORMALIZED TO 100 KM. SAMPLE SIZE: 33.

| Parameter | Value |
|---|---|
| Width of the initial half cycle (T1) | 12.7 ± 6.1 μs |
| Width of the second half cycle (T2) | 13.0 ± 5.9 μs |
| 50-50% Width of first cycle (HPBW) | 5.5 ± 2.8 μs |
| 10-90% Rise time of first cycle (R1) | 6.4 ± 3.8 μs |
| Peak of the initial half cycle (A1) | 1.4 ± 0.5 V/m |
| Peak of the second half cycle (A2) | -0.85 ± 0.47 V/m |
| Ratio of initial to secondary peak (A1/A2) | 1.8 ± 0.6 |

The similarity between the electric field signatures associated with upward and downward negative leaders is interesting, considering the differences in the conditions of their initiation, especially the presence of grounded metallic structure in the case of upward leaders.

## V. CONCLUSIONS

Simultaneous channel-base currents and distant electric fields for five upward positive flashes recorded at the Säntis tower in Summer 2014 were analyzed and compared with available data on downward leaders in negative cloud-to-ground lightning. Similarities were observed between the two processes in terms of the presence of Clarence and Malan's Breakdown, Intermediate, and Leader phases and the presence of pulses having a bimodal width distribution. Our observations thus suggest similarity between these two processes. However, more thorough observations and analyses are required to draw a firm conclusion.

## VI. AKNOWLEDGMENTS


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## REFERENCES


[1] K. Berger, “The Earth flash,” in *Lightning*, R. Golde, Ed. New York: Academic, 1977, pp. 119–190.

[2] H. Zhou, G. Diendorfer, R. Thottappillil, H. Pichler, and M. Mair, “Characteristics of upward positive lightning flashes initiated from the Gaisberg Tower,” *J. Geophys. Res. Atmos.*, vol. 117, no. D6, Mar. 2012.

[3] C. Romero, F. Rachidi, M. Rubinstein, M. Paolone, V. A. Rakov, and D. Pavanello, “Positive lightning flashes recorded on the Säntis tower from May 2010 to January 2012,” *J. Geophys. Res. Atmos.*, vol. 118, no. 23, pp. 12879–12892, Dec. 2013.

[4] M. Miki, T. Miki, A. Asakawa, and T. Shindo, “Characteristics of Negative Upward Stepped Leaders in Positive Upward Lightning,” *XV Int. Conf. Atmos. Electr. Norman, Oklahoma, U.S.A.*, no. June, pp. 15–20, 2014.

[5] D. Wang, N. Takagi, T. Watanabe, H. Sakurano, and M. Hashimoto, “Observed characteristics of upward leaders that are initiated from a windmill and its lightning protection tower,” *Geophys. Res. Lett.*, vol. 35, no. 2, pp. 19–23, 2008.

[6] F. H. Heidler, M. Manhardt, and K. Stimper, “Characteristics of Upward Positive Lightning Initiated From the Peissenberg Tower, Germany,” *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 1, pp. 102–111, Feb. 2015.

[7] J. D. Hill, M. A. Uman, and D. M. Jordan, “High-speed video observations of a lightning stepped leader,” *J. Geophys. Res. Atmos.*, vol. 116, no. 16, pp. 1–8, 2011.

[8] B. F. J. Schonland, *The Lightning Discharge, Handbuch der Physik*. New York: Springer, 1956.

[9] Y. Pu, R. Jiang, X. Qie, M. Liu, H. Zhang, Y. Fan, and X. Wu, "Upward negative leaders in positive triggered lightning: Stepping and branching in the initial stage," *Geophys. Res. Lett.*, vol. 44, no. 13, pp. 7029–7035, Jul. 2017.

[10] W. R. Gamerota, V. P. Idone, M. A. Uman, T. Ngin, J. T. Pilkey, and D. M. Jordan, "Dart-stepped-leader step formation in triggered lightning," *Geophys. Res. Lett.*, vol. 41, no. 6, pp. 2204–2211, Mar. 2014.

[11] N. D. Clarence and D. J. Malan, "Preliminary discharge processes in lightning flashes to ground," *Q. J. R. Meteorol. Soc.*, vol. 83, no. 356, pp. 161–172, Apr. 1957.

[12] D. E. Proctor, R. Uytenbogaardt, and B. M. Meredith, "VHF radio pictures of lightning flashes to ground," *J. Geophys. Res.*, vol. 93, no. D10, p. 12683, 1988.

[13] M. Stolzenburg, T. C. Marshall, S. Karunarathne, N. Karunarathna, L. E. Vickers, T. A. Warner, R. E. Orville, and H. D. Betz, "Luminosity of initial breakdown in lightning," *J. Geophys. Res. Atmos.*, vol. 118, no. 7, pp. 2918–2937, 2013.

[14] D. Petersen and W. H. Beasley, "High-Speed video observations of the preliminary breakdown phase of a negative Cloud-to-Ground lightning flash," in *XV International Conference on Atmospheric Electricity*, 2014, no. June, pp. 15–20.

[15] L. Z. S. Campos and M. M. F. Saba, "Visible channel development during the initial breakdown of a natural negative cloud-to-ground flash," *Geophys. Res. Lett.*, vol. 40, no. 17, pp. 4756–4761, 2013.

[16] A. Nag and V. A. Rakov, "A unified engineering model of the first stroke in downward negative lightning," *J. Geophys. Res. Atmos.*, vol. 121, no. 5, pp. 2188–2204, Mar. 2016.

[17] S. Karunarathne, T. C. Marshall, M. Stolzenburg, and N. Karunarathna, "Modeling initial breakdown pulses of CG lightning flashes," *J. Geophys. Res. Atmos.*, vol. 119, no. 14, pp. 9003–9019, 2014.

[18] C. L. Da Silva and V. P. Pasko, "Physical mechanism of initial breakdown pulses and narrow bipolar events in lightning discharges," *J. Geophys. Res. D Atmos.*, vol. 120, no. 10, pp. 4989–5009, 2015.

[19] W. Rison, P. R. Krehbiel, M. G. Stock, H. E. Edens, X.-M. Shao, R. J. Thomas, M. A. Stanley, and Y. Zhang, "Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms," *Nat. Commun.*, vol. 7, p. 10721, Feb. 2016.

[20] C. Romero, M. Paolone, M. Rubinstein, F. Rachidi, A. Rubinstein, G. Diendorfer, W. Schulz, B. Daout, A. K??lin, and P. Zweiacker, "A system for the measurements of lightning currents at the S??ntis Tower," *Electr. Power Syst. Res.*, vol. 82, no. 1, pp. 34–43, 2012.

[21] M. Azadifar, F. Rachidi, M. Rubinstein, M. Paolone, V. A. A. Rakov, D. Pavanello, S. Metz, and C. Romero, "Characteristics of electric fields of upward negative stepped leaders," in *International Symposium on Lightning Protection (XIII SIPDA)*, 2015, pp. 32–36.

[22] S. Karunarathne, T. C. Marshall, M. Stolzenburg, and N. Karunarathna, "Modeling initial breakdown pulses of CG lightning flashes," *J. Geophys. Res. Atmos.*, vol. 119, no. 14, pp. 9003–9019, 2014.

[23] A. Nag and V. A. Rakov, "Pulse trains that are characteristic of preliminary breakdown in cloud-to-ground lightning but are not followed by return stroke pulses," *J. Geophys. Res. Atmos.*, vol. 113, no. 1, pp. 1–12, 2008.

[24] A. Nag and V. A. Rakov, "Electric Field Pulse Trains Occurring Prior to the First Stroke in Negative Cloud-to-Ground Lightning," *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 1, pp. 147–150, 2009.

[25] V. A. Rakov, M. A. Uman, G. R. Hoffman, M. W. Masters, and M. Brook, "Bursts of Pulses in Lightning magnetic Radiation: Observations and lications for Lightning Test Standards," *JEEE Trans. Electromagn. Compat.*, vol. 38, no. 2, 1996.