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Modeling of the Stepping Process of Negative Lightning Stepped Leaders

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***Abstract*— A physical model based on the mechanism observed in experimental investigations is introduced to describe the formation of negative leader steps. Starting with a small length of a space leader located at the periphery of the negative streamer system of the stepped leader the model simulates the growth and the subsequent formation of the leader step. Based on the model, the average step length, the average step forming time and the average stepped leader propagation speed is estimated as a function of prospective return stroke peak current. The results show that the average step length and the average leader speed increases with increasing prospective return stroke current. The results also show that the speed of the stepped leader increases as it approaches the ground. For a 30 kA prospective return stroke current the average leader speed obtained is about 5 x 10^5 m/s and the average step length was about 10 m. The results obtained are in reasonable agreement with the experimental observations.**

Keywords: Lightning, Stepped leader, Space leader, Space stem

1. Introduction

About 90% of lightning ground flashes transport negative charge to Earth and they are called negative ground flashes. Return strokes of negative ground flashes are initiated by stepped leaders that travel from cloud to ground. Photographic evidence show that these leaders travel towards ground in intermittent steps and experimental data on the time intervals between the steps and the lengths of the individual steps are available in the literature [1,2]. The available information show that the time interval between steps span from 10 µs to 100 µs and the lengths of the steps span from 5 m to about 200 m [1,2,3,4]. More recently, detailed development of the stepping process in negative lightning leaders has been observed using high speed photography [4].

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The first detailed information concerning the development of negative leaders in laboratory sparks were obtained by the group of scientists working at Renadieres [5]. More details concerning the development of negative leaders were obtained in experiments conducted by Castellani et al. [6] where the bi-directional development of the leader steps were identified. Based on the experimental data obtained at Renadieres [5], Bacchiega [7] developed the first theoretical model of the stepped leader in long air gaps. The first application of the available experimental data to develop a negative lightning stepped leader model was conducted by Lalande et al. [8]. In that study the negative stepped leader model was used to simulate the properties of the negative counterpart of a bidirectional leader in an altitude triggered lightning. Based on the work of Bacchiega [7] and Lalande et al. [8], Mazur [9] developed a stepped leader model to study the attachment of negative ground flashes to grounded structures. However, in that study no information concerning the step lengths and time interval between steps is not presented. The theory developed by Lalande et al. [8] was used by Arevalo and Cooray [10] to develop a models for negative leaders in laboratory sparks. In this model a novel procedure was used to calculate the charge in the negative streamer region of the negative stepped leader. Another study to simulate the negative lightning leader was introduced by Beroual et al. [11]. In this study, the stepped leader was simulated by an electrical network, the parameters of which were extracted from electromagnetic wave propagation and experimentally observed properties of the negative leaders.

There are several leader progression models that have been developed to analyse the attachment of stepped leaders to grounded structures. These models treat the stepped leader as a charged channel that propagates continuously from cloud to ground [12,13,14]. Development of these models further requires more detailed representation of the stepped leader including its stepping process.

As mentioned earlier, the parameters that can be extracted from photography and electric field measurements are the average speed of leaders, the step lengths and the time interval between steps. The review of current literature given above shows that none of the work pertinent to lightning leaders presented so far has provided information concerning these parameters that could be tested easily against available experimental data. The goal of the present study is to introduce a stepped leader model based on the experimental observations to study how the parameters of stepped leaders such as the average speed, the step length and the interval between steps of stepped leaders vary as a function of stepped leader length and the prospective return stroke current of the stepped leader.

The paper is organized as follows. First a description of the mechanism of laboratory and lightning stepped leaders observed experimentally is provided. This section is followed by a detailed description of the model to be used in extracting lightning leader parameters. In the third section the model is exercised to generate parameters pertinent to stepped leaders and a comparison of these parameters with experimental observations is provided. This section is followed by a conclusion.

2. Mechanism of the stepping process of the stepped leader

Information gathered from long sparks show that the stepping process in negative leaders is mediated by space stems and space leaders that do not exist in the positive breakdown [5]. The mechanism is the following. Together with the formation of a negative leader step a burst of negative streamer discharges extend from the tip of the newly created leader step. Close to the extremity of the streamer region a bright spot appears and it is called a space stem. From this space stem streamers of both polarities develop in opposite directions. The positive streamers propagate towards the tip of the negative leader and the negative streamers in the opposite direction. The positive streamers from the space stem are actually propagating through the negative streamer region generated during the formation of the last step of the stepped leader. These streamer discharges converts the space stem to a space leader. The space leader elongates in both direction with one end travelling towards the tip of the negative stepped leader (i.e. tip of the last step) and the other end away from it. As the space leader approaches the tip of the negative leader its speed increases exponentially. The connection of the space leader with the tip of the stepped leader is accompanied by a simultaneous illumination of the whole space leader channel starting from the meeting point. This illumination is associated with a process that transforms the space leader into a part of the stepped leader channel. As a result the negative leader length increases by an amount equal to the length of the space leader. During this conversion process a burst of negative corona emanates from the new tip of the negative leader (i.e. the rear end of the space leader that travelled away from the stepped leader). At the extremity of this streamer region a new space stem is created and the process is repeated. Recently, the stepping process in negative stepped leaders in laboratory were studied with extremely high resolution in a study conducted by Kochkin et al. [15]. This study confirms the bidirectional nature of the discharge. Moreover, the study shows that fully extended negative streamers leave behind luminous regions (called beads in that study) on their path and some of these beads give rise to the space stems.

Recent experimental data show that a mechanism similar to what is being observed in laboratory sparks is also active in lightning stepped leaders [3,4]. The data shows that a lightning leader step is also created by a space leader that starts ahead of the current head of the negative leader. When this space leader meets the existing stepped leader a new step is created. This process is shown

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in Figure 1 which was adapted from reference [4]. This photograph shows clearly the development of the space leader and the subsequent development of the step.

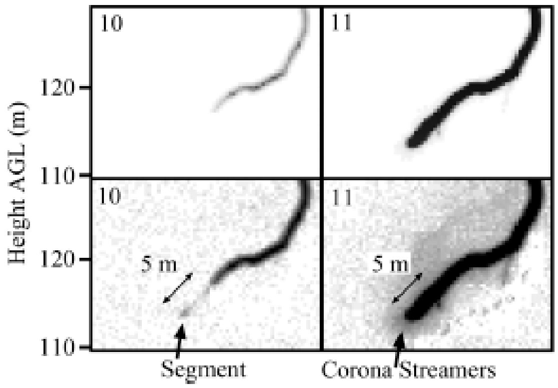

Figure 1: The formation of a leader step as observed in the negative leader of an altitude triggered lightning. The lower set of diagrams show the contrast enhanced picture of the upper set. Observe the high luminosity region located ahead of the leader tip in the lower left diagram which is probably the space leader. The lower right diagram shows the newly formed leader step together with the streamers that emanated from the tip of the leader. Adapted from [4].

3. The model

As observed in the experiments and described in the last section, the stepping process of the negative stepped leader starts with the creation of a space stem and a space leader (called a pilot system) and the stepping process will be completed when the space leader reaches the tip of the negative stepped leader. To the best of our knowledge the exact mechanism that gives rise to the space stem and the subsequent space leader is not known. Moreover, sufficient experimental data that can be used to create and test a model for the space stem and its subsequent conversion to the space leader is not available. For this reason in the model the presence of a short length space leader is assumed a priori.

The simulation starts when the down coming stepped leader has extended to a given length, say L_l, below the negative charge centre. The various steps of the simulation are the following:

1) Assuming that the leader channel is straight and vertical, the charge deposited along the length L_l of the leader channel is estimated using the analytical equations given in Cooray et al. [16]. These analytical equations provide the distribution of the

linear charge density along the channel of a stepped leader with a given prospective return stroke current. Using this charge distribution the electric field ahead of the stepped leader channel is estimated.

2) The experimental data show that negative streamers require a background electric field of about 1 – 2 x 10^6 V/m for stable propagation [5]. In the simulations this field is assumed to be 1.5 x 10^6 V/m. From the calculated electric field distribution ahead of the leader tip the point where the electric field decreases beyond the value 1.5 x 10^6 V/m is obtained. It is assumed that this point defines the boundary of the negative streamer region. Let us represent the distance from the tip of the leader to this point by L_s.

3) The negative streamers emanating from the negative leader tip maintains a constant potential gradient in the negative streamer region. Experimental data show that this potential gradient is also equal to about 1 – 2 x 10^6 V/m [5,17]. Based on this, in the simulation we assume that in the negative streamer region (marked in Figure 2) the potential gradient has a value equal to 1.5 x 10^6 V/m. In the analysis it is assumed that the electron avalanche will be converted to a streamer when the number of positive ions at the head of the avalanche exceeds about 10^8 [17]. The simulation continues using the time varying electric field of the stepped leader until the streamer inception criterion is satisfied.

4) The charge in the negative streamer burst generated from the space leader is calculated following the procedure outlined in references [14]. The charge associated with these streamer bursts are calculated using a distance-voltage diagram with the origin at the tip of the grounded conductor as follows. The procedure is illustrated in Figure 3. The streamer zone is assumed to maintain a constant potential gradient E_{str}. In the distance-voltage diagram this is represented by a straight line. On the same diagram the background potential produced by the thundercloud and the down-coming stepped leader at the current time is depicted. If the area between the two curves up to the point where they cross is A (see Figure 3), the charge in the streamer zone is given by

$$Q_{ns} \approx K_Q A \qquad (1)$$

where K_Q is a geometrical factor. Becerra and Cooray [14] estimated its value to be about 3.5 x 10^{-11} C/V.m.

5) Since there is no source for the charges that are being deposited in the streamer channels created by the space stem and the space leader, the discharge propagates as a bi-directions leader with a net zero charge. For example, the charge necessary for the propagation of positive streamers are provided by the negative streamers which remove negative charge from the space leader and

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leave behind positive charge that is being utilized in the creation of positive streamers. The charging of the space leader due to the removal of negative charge from the negative streamer burst will give rise to a burst of positive streamers. Assuming net zero charge on the space leader the charge associated with the positive streamer burst, Q_{ps}, assumed to be equal to Q_{ns}.

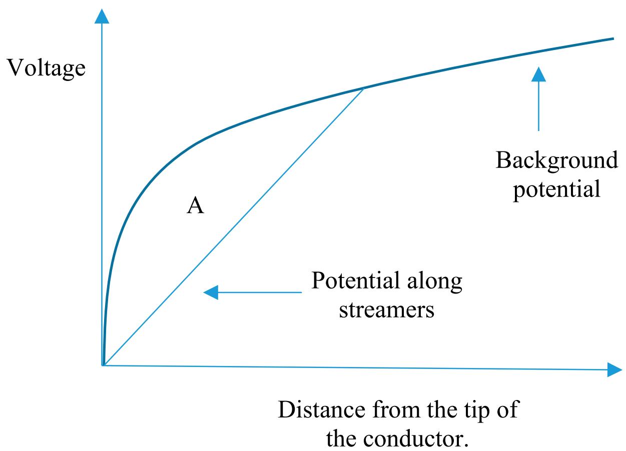

Figure 2: Distance-Voltage diagram that illustrates how the charge associated with a streamer burst is obtained. The area between the two curves representing the background potential and the streamer potential is marked A.

6) The currents associated with the streamer bursts convert their stems into hot channels and they become part of the space leader. This leads to the elongation of the space leader. Following the procedure introduced in reference [17], the extension of the negative and positive tips of the space leader is assumed to be $|Q_{ns}|/q_l$ where q_l is the charge necessary to thermalize a unit length of the leader channel. Based on the theory of Gallimberty [17] it is assumed to be equal to 60 µC/m. This completes one cycle of the numerical simulation. The time taken for this cycle is estimated by taking into consideration the length of the negative and positive streamer bursts from the space leader and dividing these distances by the speed of negative streamers. The experimental data obtained with high speed cameras shows that fully developed positive streamers can propagate at speeds close to about 4 x 10^6 m/s and the speed of negative streamers is about 25% lower than the speed of positive streamers [18]. Since the streamers in streamer bursts associated with lightning are rather long in the simulation we assume the positive and negative streamer speeds to be 10^6 m/s and 4 x 10^6 m/s. Observe that positive streamers are propagating in over-voltage condition because they are moving in a region where the electric field is larger than the electric field necessary for stable positive streamer

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propagation. Their propagation is limited only by the charge made available to it by the negative streamers. Thus the length of the positive streamer is estimated again from a curve similar to that in Figure 3 but from the known value of the area. The time necessary for this cycle of physical process i.e. from one inception of negative corona from the negative tip of the space leader to the next streamer inception is given by

$$t_c = l_{ns} / v_{ns} + l_{ps} / v_{ps} \quad (2)$$

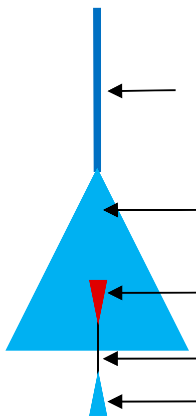

Figure 3: Intermediate stage of the numerical simulation of the negative leader propagation.

The cycle is repeated again using the new space leader length as the initial value. The procedure continues until the space leader meets the tip of the negative stepped leader. When this happens the stepped leader is assumed to extend to a distance equal to the length of the space leader. The time necessary for the development of the step once the space leader meets the stepped leader tip is neglected in calculating the speed of stepped leaders. The total time necessary for the initiation of the step is given by

$$T_{step} = \sum_{m=1}^{m=n} t_{cm}$$

In the above n is the total number of cycles necessary for the space leader to reach the tip of the stepped leader and t_{cm} is the time as defined by Equation 2 to complete the mth cycle.

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Once the new step is formed, the streamer length associated with the new extension of the stepped leader is estimated as before and the procedure is repeated again. It is important to mention here that in the simulation the space leader is assumed to have a rather high conductivity so that it can be considered as a good conductor in estimating the electric fields at its tips which are necessary in calculating the length of streamer regions and the electric field through which the negative streamers from the space stem are propagating.

4. Results

The stepped leader charge distribution model as developed by Cooray et al. [16] gives the distribution of the stepped leader charge as a function of the height of the stepped leader tip above ground. Thus the electric field in front of the stepped leader channel when its tip is at a given height from ground level, a parameter necessary as an input to the stepped leader model, is evaluated using this model. Combining this with the stepped leader model the step length, the step forming time and the average stepped leader speed was calculated as a function of the height of the stepped leader tip for several prospective return stroke currents. Before presenting these results, let us consider first the available information concerning the stepped leaders.

Significant amount of experimental data are available on the step length, stepping interval and the average speed of stepped leaders. The data published before the year 2000 show that the length of stepped leaders vary between 8.5 m to 200 m [1, 2,18,19], the step intervals vary between 5 µs to 200 µs [1,2,18,19,20,21] and the average leader speeds vary between 0.8 x 10^5 m/s to 1.5 x 10^6 [1, 2, 18, 19, 21, 22]. Recent high speed video measurements of Hill et al. [4] found the average step interval of 16.4 µs and average step length of 5.2 m for 82 steps. In the case of an altitude triggered lightning Biagi et al. [3] found the step lengths to be 5 m to 8 m in length. The time interval between steps can also be obtained by measuring the pulse intervals between the leader pulses. The step intervals close to the return stroke, which means when the stepped leader is close to ground varied between about 15 µs to 3 µs [23, 3]. A statistical significant study on the speed of stepped leaders were conducted recently by Campos et al. [24]. They found average speeds of 3.4 x 10^5 m/s and 1.87 x 10^5 m/s at two sites, one in Southern Brazil and the other in Arizona. The maximum and minimum speeds observed were 0.9 x 10^5 m/s and 1.98 x 10^6 m/s. They also found that about 42% of the leaders showed speeds to increase as the leader extends and 49% showed irregular behaviour. Only 9% showed a decrease in speed with increasing leader length. Campos et al. [24] also analysed how the leader speed is related to the return stroke peak current. Even though there is some scatter there was a clear indication that the leader speeds increase with increasing peak current.

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The results are obtained for four prospective return stroke currents with peaks 15 kA, 30 kA, 45 kA and 60 kA. In the simulation step lengths are calculated for step leader lengths from 2500 km to 4750 km. The total length of the channel selected in the calculation is 5 km. Moreover, the calculations were conducted for three values of negative streamer speeds, namely, 0.5 x 10^6 m/s, 10^6 m/s and 2 x 10^6 m/s. Furthermore, two sets of calculations were conducted one for the negative streamer potential gradient of 10^6 V/m and the other for 2x10^6 V/m. Let us consider the results obtained for leader step length, stepping time and the speed of the leader separately.

4.1 Step length

The results of the calculation show that the step length is independent of the speed of negative streamers. It is only controlled by the streamer potential gradient. This is understood because the streamer gradient decides the length of the streamer region and this is directly related to the step length. On the other hand the streamer speed controls the time necessary for the formation of the step. The average step length as a function of peak current is shown in Figure 4a for E_{str} = 10^6 V/m and Figure 4a for E_{str} = 2 x 10^6 V/m. First observe that the step length increases with increasing peak current. The reason for increasing step length with

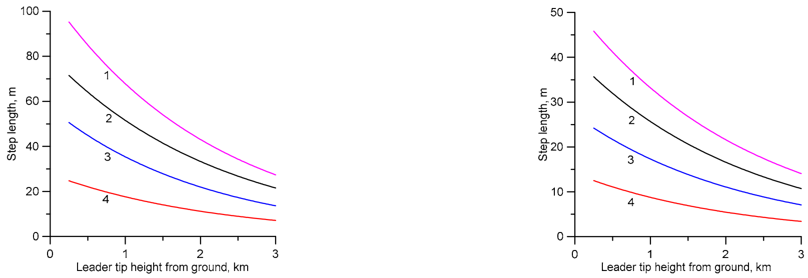

Figure 4: Step length as a function of the height of the leader tip for four different current peaks. (1) 60 kA, (2) 45 kA, (3) 30 kA and (4) 15 kA. Calculated assuming (a) E_{str} = 10^6 V/m and (b) E_{str} = 2 x 10^6 V/m.

increasing peak current can be understood when one notice that the length of the streamer region ahead of the leader channel increases with increasing prospective return stroke current. Second observe that the step length increases as the stepped leader approaches the ground. This is caused by the increase in charge density at the leader tip as it approaches the ground. Third, note that for a given current the step length decreases as the potential gradient of the streamer increases. As mentioned previously this is caused by the decrease in streamer length with increasing streamer potential gradient.

4.2 Step forming time

Results show that the step forming time is affected both by the prospective peak current, speed of negative streamer and the potential gradient of the streamer. For this reason in addition to the calculations conducted with two streamer potential gradients calculations are conducted also for three negative streamer speeds. The results are presented in Figure 5 and Figure 6. Observe

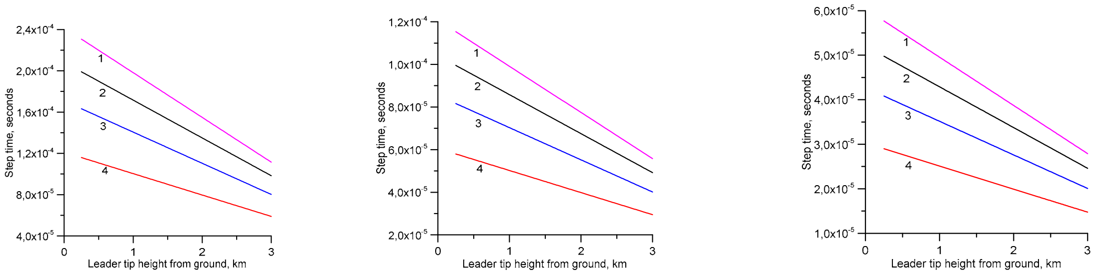

Figure 5: Step forming time as a function of leader tip height from ground level for four different prospective return stroke currents. (1) 60 kA, (2) 45 kA, (3) 30 kA and (4) 15 kA. Results are shown for three different negative streamer speeds, namely, (a) 0.5 x 10^6 m/s, (b) 1.0 x 10^6 m/s and (c) 2.0 x 10^6 m/s. Calculations are for E_{str} = 10^6 V/m.

that the step forming time depends both on the prospective peak current, the potential gradient of the negative streamers and their speed. As mentioned earlier the time it takes to make a step depends on several events. First, it depends on the time it takes for the negative streamers issued from the new leader tip to reach their full length where the formation of the space leader takes place. Once the space leader is formed depending on the field configuration and the distance to the tip of the stepped leader it requires several bursts of negative streamers before the space leader can reach the tip of the stepped leader. During each burst negative streamer travel from the tip of the space leader to a point where it expends all the potential difference available for its propagation. This propagation of the negative streamers also require some time depending on their speed. The time necessary for the formation of a step is given by the sum of these times. The step time increases with increasing peak current because the length of the streamer region increases with increasing charge on the leader channel. For the same reason the step forming time increases as the leader approaches the ground. However, for a given height and a current this time decreases with increasing streamer potential gradient and it increases with decreasing streamer speeds. It decreases with increasing potential gradient because the length of the streamers and hence the time necessary for the streamers of a given speed to reach their final destination decreases

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with decreasing potential gradient. This time decreases with increasing streamer speed because this will reduce the travel time of the streamers.

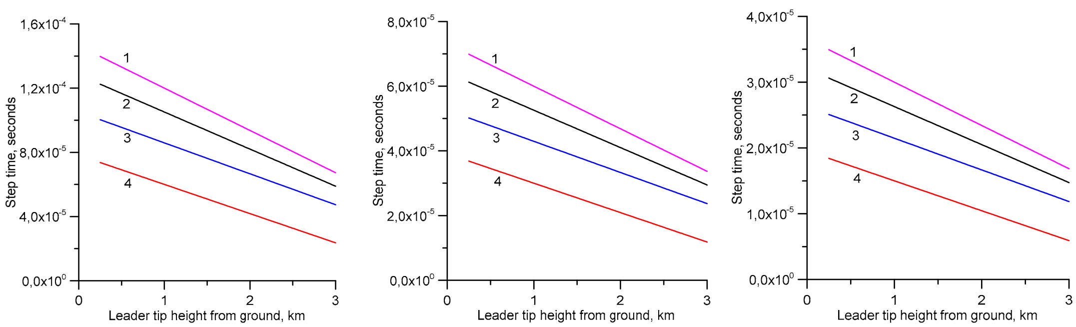

Figure 6: Step forming time as a function of leader tip height from ground level for four different prospective return stroke currents. (1) 60 kA, (2) 45 kA, (3) 30 kA and (4) 15 kA. Results are shown for three different negative streamer speeds, namely, (a) 0.5 x 10^6 m/s, (b) 1.0 x 10^6 m/s and (c) 2.0 x 10^6 m/s. Calculations are for E_{str} = 2 x 10^6 V/m

4.3 Leader speed

The speed of propagation of the leaders as a function of the height of the stepped leader tip from ground level for four different prospective return stroke currents and for different streamer parameters are shown in Figures 7 and 8. First observe that the leader

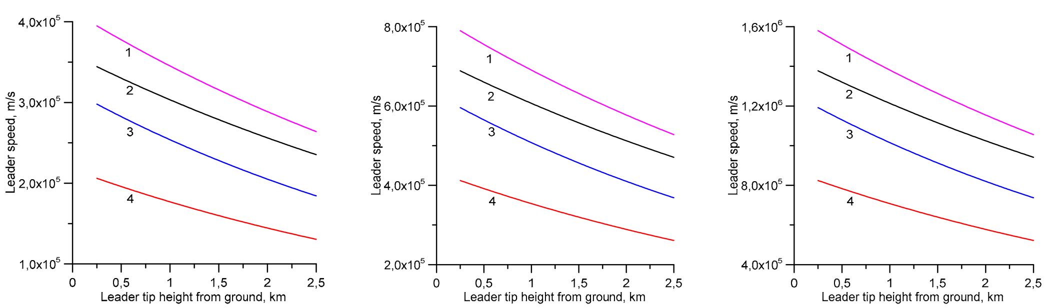

Figure 7: Leader speed as a function of leader tip height from ground level for four different prospective return stroke currents. (1) 60 kA, (2) 45 kA, (3) 30 kA and (4) 15 kA. Results are shown for three different negative streamer speeds, namely, (a) 0.5 x 10^6 m/s, (b) 1.0 x 10^6 m/s and (c) 2.0 x 10^6 m/s. Calculations are for E_{str} = 10^6 V/m.

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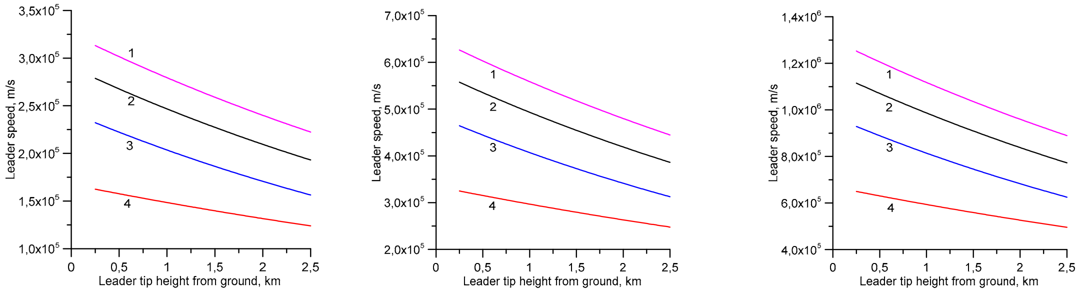

Figure 8: Leader speed as a function of leader tip height from ground level for four different prospective return stroke currents. (1) 60 kA, (2) 45 kA, (3) 30 kA and (4) 15 kA. Results are shown for three different negative streamer speeds, namely, (a) 0.5 x 10^6 m/s, (b) 1.0 x 10^6 m/s and (c) 2.0 x 10^6 m/s. Calculations are for E_{str} = 2 x 10^6 V/m.

speed increases as the stepped leader nears the ground. For a given height the leader speed increases with increasing peak current, increasing streamer speed and with decreasing streamer potential gradient. The leader speed is controlled both by the step length and the time necessary for the formation of the step. It increases with increasing streamer speed because the latter will reduce the time of formation for a given step length. However, it is the change in step length that influence the leader speed more than the time of formation. This is the reason why the parameters that increase the step length, i.e. larger peak current and lower potential gradient, lead to larger leader speeds. The data presented above gives the instantaneous speed at a given level. What is being measured usually is the average speed. In order to generate data that can be compared directly with experimental data the average speed over the last two kilometres is estimated and its value is tabulated in Table 1. Observe again that the average speed increases with increasing peak current, increasing streamer speed and decreasing potential gradient.

5. Discussion

The calculated step lengths for different possible streamer parameters are distributed over the range of 5 m to 200 m for different currents, the step forming times are distributed over the range 10 to about 200 µs and the average speeds are distributed over the range of 10^5 m/s to about 1.6x10^6 m/s. This shows given the possibility of varying parameters the calculations produce results in the same ballpark as the measurements. According to the results presented in Figure 8, the leader speed increases as the leader approaches the ground. However, in experimental data only about 42% of the leaders show such a tendency. One possible reason

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for this discrepancy is the following. In the calculations we assume that the leader charge increases continuously as the stepped

Table 1: Average speed of the stepped leader over the last 2 km for different values of prospective peak current, streamer speed and streamer potential gradient.

Streamer potential gradient: 1.0 x 10^6 V/m					
Streamer speed: 0.5x10^6 m/s		Streamer speed: 0.5x10^6 m/s		Streamer speed: 0.5x10^6 m/s	
Peak current (kA)	Leader speed (m/s)	Peak current (kA)	Leader speed (m/s)	Peak current (kA)	Leader speed (m/s)
15	1.672x10^5	15	3.34x10^5	15	6.69x10^5
30	2.384x10^5	30	4.76x10^5	30	9.53x10^5
45	2.908x10^5	45	5.81x10^5	45	11.67x10^5
60	3.277x10^5	60	6.55x10^5	60	13.11x10^5
Streamer potential gradient: 2.0 x 10^6 V/m					
Streamer speed: 0.5x10^6 m/s		Streamer speed: 0.5x10^6 m/s		Streamer speed: 0.5x10^6 m/s	
Peak current (kA)	Leader speed (m/s)	Peak current (kA)	Leader speed (m/s)	Peak current (kA)	Leader speed (m/s)
15	1.43x10^5	15	2.86x10^5	15	5.72x10^5
30	1.94x10^5	30	3.88x10^5	30	7.76x10^5
45	2.359x10^5	45	4.71x10^5	45	9.438x10^5
60	2.689x10^5	60	5.379x10^5	60	10.75x10^5

leader approaches the ground. This is correct if we consider a straight vertical stepped leader. However, in the presence of branches the electric field configuration could be very complex and it is possible that specially in the vicinity of the branches there is a certain amount of screening and this may cause some form of modulation of the charge and this in turn can make the speed to increase over some regions and then to decrease in other regions. This complex behaviour is actually observed in 46% of the stepped leaders. If we consider the average stepped leader speed observed over the last 2000 m or so in the study conducted by Campos et al. [24] the observed value is about 3 x 10^5 m/s. This shows within the confines of the present leader model the best parameters that approximate the experimental data are 2.0 x 10^6 for the streamer speed and 2.0 x 10^6 V/m for the streamer gradient. The leader step is also controlled by the charge on the leader and if the charge is modulated along the channel it will also modulate the length of the leader steps. For the parameters mentioned above the leader step length close to ground is in the order

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of about 10 m and this agrees to some extent with the results presented by Berger [2]. For the parameters mentioned earlier the stepping time close to ground is about 20 µs and it decreases with increasing height. This value too is in reasonable agreement with the experimental data of Berger [2]. Unfortunately, almost all the studies do not give the prospective peak current and for this reason a direct comparison is impossible in the present study. The study also shows that the leader speed increases with increasing peak current and this tendency is also observed in the experimental data of Campos et al. [24].

Let us now consider some of the assumptions made in the stepped leader model. In constructing the model we have made several assumptions and let us consider these assumptions here. In the model we assume that the space leader is created at the very edge of the streamer region and only one such leader is created. It is possible that the space leader is created when the negative streamer charge reaches a certain critical value and it may occur in lightning before the streamers travel the full length. If this the case both the calculated step lengths and step times will decrease because the origin of the space leader takes place closer to the leader tip than assumed in the model. In the model it is assumed that only one space leader is created but in reality several space leaders could be created. In this case the leader may produce two branches. Thus the results are valid for the stepped leaders away from the branch points. This is also the case as mentioned before close to the branch points the screening of the channels from each other may reduce the charge on the leader. In the model we have neglected the time necessary for the propagation of the positive leader. Experimental data show that even in virgin air under identical conditions the negative streamers have about 25% of the speed of positive streamers. If we assume the positive streamers to be four times faster than the negatives our results would be changed only marginally. However, in the present situation they are moving in regions of opposite charge density and in fields which are much larger than their stability fields. Thus the assumption that they move very fast compared to positive and the time necessary for them is much smaller than the time taken by negative streamers is justified. In the calculation we have assumed that the space leader channel has a fixed radius and that it can be treated as a good conductor. Even though it will increase the complexity of the model and the computation time it can be corrected. For example the theory of Gallimberti [17] shows how the leader radius increases as a function of the energy input to the leader and how the leader potential will decrease with time as the current passing through it increases. This theory can be applied to the space leader to consider the variation of the leader potential and the radius. The introduction of this to the model is under investigation. In the model we have assumed that the space leader is created almost instantaneously as the streamers extends to their extreme limits. However, space leader is created through the action of a space stem and this process may take some time which is neglected in the simulation. However, if the space stem is

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created before the streamers reaches their outer extremes it will speed up the process and these two assumptions may compensate each other.

6. Conclusions

A model developed based on the mechanism observed for the formation of steps in the laboratory and in the field is shown to be capable of generating the lengths of the steps, the speed of the leader and the spatial variation of the leader as a function of prospective return stroke current. Both the step length and the average speed increases with increasing prospective return stroke current. The model also predict that the stepped leader speed will increase as it approaches the ground. The results depends on the streamer speeds and streamer potential gradients assumed in the model. The best results are obtained when the streamer gradient is 2 x 10^6 V/m and the streamer speed is about 10^6 m/s. Under these assumptions the model predicts that a stepped leader with a 30 kA prospective return stroke current may produce steps of about 15 m in length close to ground and the average speed of propagation of about 5 x 10^5 m/s. The ranges of step lengths, step times and leader speeds obtained from the stepped leader model developed in this paper agree reasonably well the average speed and the step length observed in experimental investigations.

7. References

[1] Schonland, B. F. J., D. J. Malan, and H. Collens (1935), Progressive lightning II, Proc. R. Soc. London, Ser. A, 152, 595‐625, doi:10.1098/ rspa.1935.0210.

[2] Berger, I. (1967), Novel observations on lightning discharges: Results of research on Mount San Salvatore, J. Franklin Inst., 283, 478 – 525, doi:10.1016/0016-0032(67)90598-4.

[3] Biagi, C. J., M. A. Uman, J. D. Hill, D. M. Jordan, V. A. Rakov, and J. Dwyer (2010), Observations of stepping mechanisms in a rocketand ‐ wire triggered lightning flash, J. Geophys. Res., 115, D23215, doi:10.1029/2010JD014616.

[4] Hill, J.. D., M.. A. UMAN, and D.. M. JORDAN, High-speed video observations of a lightning stepped leader", Journal of Geophysical Research-atmospheres, vol. 116, pp. D16117, aug, 2011.

[5] Les Renardières Group 1978 Negative discharges in long air gaps at les Renardieres. Electra WG N 33.01.

[6] Castellani A., Bondiou A, Lalande P, Bonamy A and Gallimberti I, 1998, Laboratory study of the bi-leader process from an electrically floating conductor Part 2: Bileader properties. IEE Proc. Sci Meas Technol, Vol 145, No.5, September.

Peer-reviewed version available at *Atmosphere* **2017**, *8*, 245; doi:10.3390/atmos8120245

[7] Bacchiega G, Gazzani A, Bernardi M, Gallimberti I and Bondiou A 1994 Theoretical modelling of the laboratory negative stepped leader, Proceedings of the 1994 International Aerospace and Ground Conference on Lightning and Static Electricity, Mannheim, Germany.

[8] Lalande P, Bondiou-Clergerie A, Bacchiega G and Gallimberti I. 2002 Observations and modeling of lightning leaders. C R Physique 3 1375 - 92.

[9] Mazur V, Ruhnke L, Boundiou-Clergerie and Lalande P, 2000, Computer simulation of a downward negative stepped leader and its interaction with ground structures. Journal of Geophysical Research, Vol 105, No. D17, page 361 – 369. September.

[10] Arevalo, L. and V. Cooray, Preliminary study on the modelling of negative leader discharges, J. of Physics D: Applied Physics, 44(31, pp. 315204, 2011.

[11] Beroual A, Rakotonandrasana J, Fofana I 2010 Predictive dynamic model of the negative lightning discharge based on the similarity with long laboratory sparks. Part 1: physical process and modeling. IEEE Transactions on Dielectrics and Electrical Insulation Vol 17, N 5, 1551 – 1561, October.

[12] Dellera, L and Garbagnati, E, 1990, Lightning stroke simulation by means of the leader progression model. Part I: Description of the model and evaluation of free-standing structures, IEEE Transaction on Power Delivery, PWRD-5. Issue 4 pp. 2009-22.

[13] Rizk F, 1994, Modeling of lightning incidence to tall structures. Part I: Theory, IEEE Trans. Power Delivery, PWRD-9, Number 1 pp. 162–171.

[14] Becerra, M. and V. Cooray, 2006, A self consistent upward leader propagation model, J. Phys.D: Appl. Phys. 39, pp. 3708-3715.

[15] Kochkin, P., N. Lehtinen, A. P. J. van Deursen and N. Østgaard, Pilot system development in metre-scale laboratory discharge, J. Phys. D: Appl. Phys. 49 (2016) 425203 (10pp)

[16] Cooray, V., V. Rakov, N. Theethayi, The lightning striking distance –revisited, J. Electrostatics, Vol. 65, 5-6, pp. 296–306, 2007.

[17] Gallimberti I 1979 The mechanism of long spark formation, Journal de Physique Colloque C7, Suppl. 7, Volume 40, pp. 193-249.

[18] Schonland, B. F. J. (1956), The lightning discharge, Handb. Phys., 22, 576 – 628.

Peer-reviewed version available at *Atmosphere* **2017**, *8*, 245; doi:10.3390/atmos8120245

[19] Chen, M., N. Takagi, T. Watanabe, D. Wang, Z. - I. Kawasaki, and X. Liu (1999), Spatial and temporal properties of optical radiation produced by stepped leaders, J. Geophys. Res., 104, 27,573 – 27,584, doi:10.1029/ 1999JD900846.

[20] Krider, E. P. (1974), The relative light intensity produced by a lightning stepped leader, J. Geophys. Res., 79, 4542 – 4544, doi:10.1029/ JC079i030p04542.

[21] Lu, W., D. Wang, N. Takagi, V. Rakov, M. Uman, and M. Miki (2008), Characteristics of the optical pulses associated with a downward branched stepped leader, J. Geophys. Res., 113, D21206, doi:10.1029/ 2008JD010231.

[22] Orville, R. E., and V. P. Idone (1982), Lightning leader characteristics in the Thunderstorm Research International Program (TRIP), J. Geophys. Res., 87, 11,177 – 11,192, doi:10.1029/JC087iC13p11177.

[23] Cooray, V., and S. Lundquist (1985), Characteristics of the radiation fields from lightning in Sri Lanka in the tropics, J. Geophys. Res., 90, 6099 – 6109, doi:10.1029/JD090iD04p06099.

[24] Leandro Z. S. Campos, L. Z. S., M. M. F. Saba, T. A. Warner, O. Pinto Jr., E. P. Krider, and R. E. Orville, High speed video observations of natural cloud to-ground lightning leaders-A statistical analysis, Atmospheric Research, 135-136, 285-305, 2014.