Relationship Between Continuing Current and Positive Leader Growth

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ABSTRACT: It has long been speculated that the source of continuing current (CC) for negative CG flashes is provided by the growth of the positive leader into negative charge regions. In this study, we use Langmuir Electric Field Array (LEFA) data and Lightning Mapping Array (LMA) data to investigate these speculations. LEFA data allows us to estimate the occurrence and duration of CC, while LMA data allows us to estimate channel growth throughout a flash. By connecting LMA VHF sources onto contiguous channels we inferred the growth of the positive leader for each return stroke. We sorted each return stroke by their growth rate magnitude and further identified each by their CC type. This analysis provides no identifiable correlation linking the positive leader growth rate to CC occurrence or duration. Finally, we divide the whole flash into 10 ms windows and calculate the growth rate throughout the flash for those windows. This approach allows us to observe any growth rate trends occurring before, during, or after the CC. We are unable to find any correlation, which implies that positive leader growth is not the primary mechanism that determines CC occurrence and duration.

INTRODUCTION

Cloud-to-ground (CG) flashes consist of leaders that exit the parent cloud and connect to the ground. For a negative CG (-CG), negative charge is carried to ground by a negative leader. Due to the bi-polar nature of lightning, the opposite end of the leader, typically located within the cloud, will be positively charged. When the negative leader connects to ground and causes a surge of current called the return stroke it may be followed by a steady, long-lived current called continuing current (CC). Why some return strokes are followed by CC and some are not is still not properly understood, but is thought to depend on the characteristics of the positive leader within the cloud [*Krehbiel et al.*, 1979; *Rakov and Uman*, 1990; *Mazur*, 2002; *Saba et al.*, 2006; *Williams*, 2006].

The positive leader grows by the ionization of air due to the large potential difference between the leader tip and the cloud. One can imagine that each time a positive branch ionizes air in the cloud, it is similar to adding a charged capacitor. Since the channel is grounded, there is a large electric potential difference between the old channel and the new channel which provides current to the circuit as the electric potential equalizes. This picture of connecting additional capacitors suggest that current should be proportional to some power of the growth rate. If this is the case, then there should be some measurable increase in positive leader growth during CC compared to when there is none. This is what we sought to determine.

DATA

The flashes in this study occurred around Langmuir Laboratory near Socorro, New Mexico. Data from the Langmuir Electric Field Array (LEFA, 0.3 Hz-50 kHz electric field change)[*Sonnenfeld and Hager*, 2013] and Lightning Mapping Array (LMA, 60-66 MHz VHF band) are used to analyze the dependence of CC on positive leader channel branching and growth. This study consists of nine -CG flashes which comprise 57 return strokes, 30 of which were followed by CC (10 very short, 6 short, and 14 long, as defined as having durations of 3-10 ms, 10-40 ms, and more than 40 ms, respectively).

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The LEFA data allow us to determine which return strokes were followed by CC and also the duration of the CC. We calculated continuing current duration by measuring the time interval between the return stroke field change and its intersection with interstroke field activity (which fits a straight line).

The Langmuir LMA used in this study contained over 20 stations situated around Langmuir Laboratory. The high number of instruments, along with the relatively quiet environment, gives us the sensitivity required to observe positive breakdown activity, which is much quieter in RF than the negative leader [*Thomas et al.*, 2004; *Edens et al.*, 2012]. To determine channel growth, we modify the PulseGraph function described in *Hager et al.* [2007]. This function was designed to join LMA VHF source points provided to arrive at a channel structure for a complete flash which can be used to measure channel length. It can also be used to connect new points to an existing channel as the flash progresses in order to calculate the length increase of the channel during the time interval of interest. In order to limit the number of noise solutions and prevent false channel detection by the Pulsegraph function, LMA data is filtered using relatively strict parameters of minimum number of instruments and chi squared values (typically around 12 and 0.5 respectively). Applying the PulseGraph function on the filtered LMA data provides very clean and well determined channel structure and yields more accurate channel lengths used in this analysis.

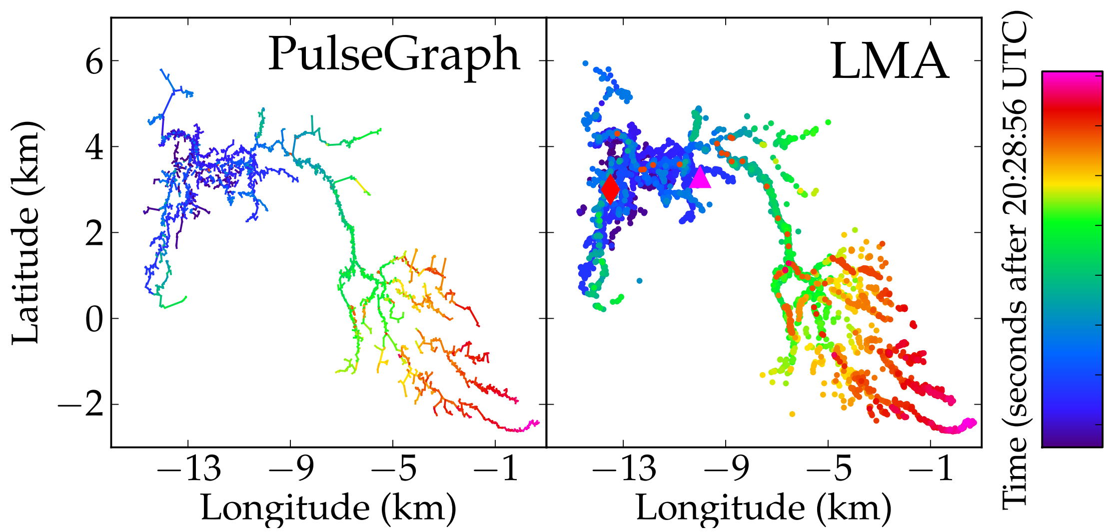

Figure 1: (Right) LMA and (left) PulseGraph plan views of a -CG flash occurring on July 8, 2013. Color represents time (shown in colorbar). The magenta triangle designates the location of the first return stroke while the red diamond represents the location of the rest of the return strokes according to NLDN data.

ANALYSIS AND DISCUSSION

We calculated a growth rate for each of the 57 return strokes using

$$R_{RS} = \frac{G}{t_{CC}},$$

where R_{RS} is the average growth rate for each return stroke, G is the estimated channel growth and t_{CC} is the return stroke and CC duration. Organizing these results into a histogram gives Figure 2. The colors in Figure 2 represent return strokes with long (red), short (green), very short (yellow), or without CC (blue). There is no preferential growth rate based on CC type as previously defined. Therefore we cannot say that longer CC corresponds with higher growth rates.

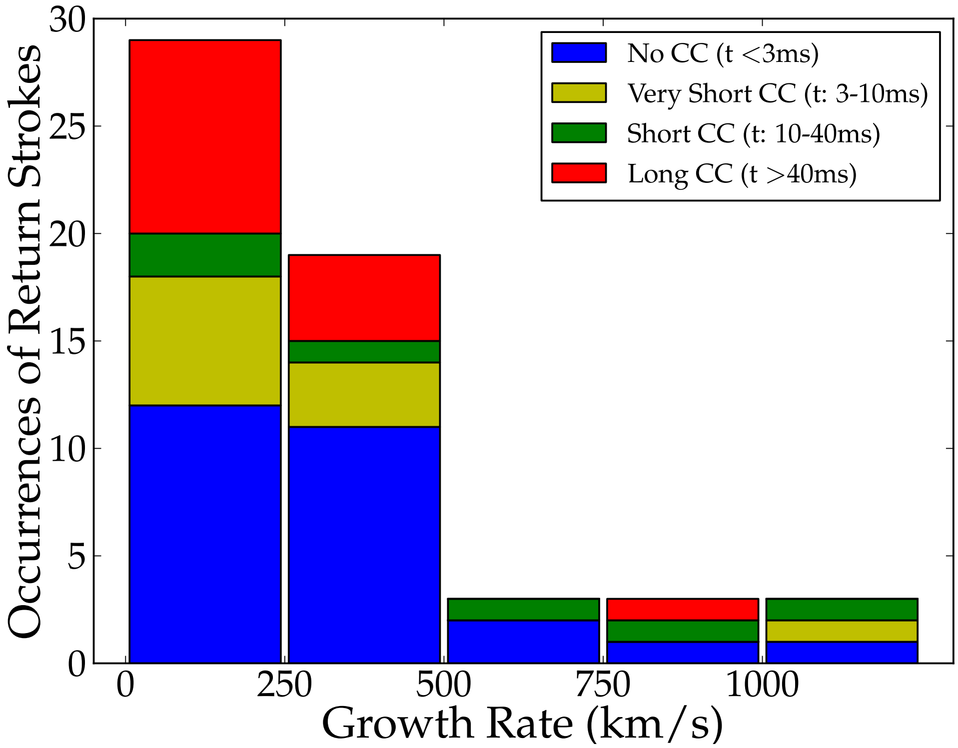

Figure 2: Histogram of the return strokes categorized by growth rate. The y-axis shows the number of return strokes (from our data set of nine flashes) that had positive channel growth rates indicated on the x-axis. The red, green, and yellow bars count long, short, and very short CC, while the blue bars represent no measurable CC (lasting less than 3 ms). The data reveals no preferential growth rate based on CC type.

In the analysis described above, the growth rates were averaged over the time frame of the return stroke and CC. However it is possible to determine the growth rate at higher time resolution. By dividing LMA data for a whole flash into 10 ms windows, the growth rate can then be calculated during those windows. Figure 3 shows the growth rate plotted above the LEFA and LMA data for the duration of the flash. This analysis can allow for possible trends to be identified throughout the flash and help to determine if there is a correlation between positive leader growth and CC not observable in the averaged growth rates from Figure 2.

Figures 1 and 3 illustrate a -CG flash occurring on July 8, 2013. This flash has seven return strokes according to NLDN data, two of which are stepped leaders connecting to ground at different locations (indicated in Figure 1). The two stepped leaders appear as maxima in channel growth on Figure 3. Inspection of the LMA data show that after the second stepped leader (approximately 1.08 seconds in Figure 3), the VHF sources primarily come from positive leader breakdown. After this time the growth rate remains constant throughout the rest of the flash. This constant growth rate persists even though the sixth and seventh return strokes are followed by long CC.

Seven of the nine flashes in this study also show constant positive leader growth rates. Although two flashes do have non constant growth rates, they showed trends that were inconsistent with the speculation that the growth of the positive leader is the source of CC. While some increases in growth rates did coincide with the occurrence of CC, others did not. Also, there were instances where long CC was accompanied by lower growth rates than shorter duration CC.

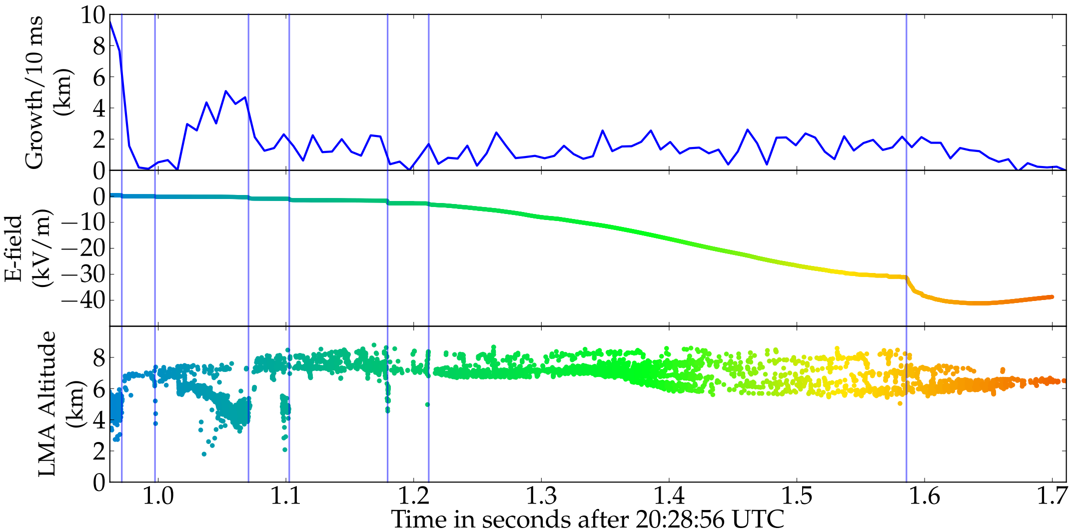

Figure 3: (Top) Growth calculated over 10 ms windows throughout the flash. (Middle) LEFA and (bottom) LMA data matched in time for a -CG occurring on July 8, 2013. The vertical lines represent the times of the seven return strokes in this flash as determined by the NLDN.

CONCLUSIONS

Using LEFA data to find CC duration and the PulseGraph function to estimate channel growth vs time, the growth of positive leaders was compared to CC occurrence and duration. We categorized each return stroke by its average growth rate and then compared return strokes having long, short, very short, or no CC. We found that there was no significant difference in growth rate based on CC type.

The growth rate throughout a flash during 10 ms windows was analyzed for the nine flashes in this study. Seven out of the nine flashes contain constant growth rates during positive leader activity even though there were occurrences of CC, while the remaining two flashes show peaks which are inconsistent with CC occurrence.

It is possible that CC is caused by growth that occurs on a small scale unresolved by the LMA. However, the conclusions from the data analyzed in this study all agree with the following, the growth of the positive leader is not the primary mechanism determining CC occurrence and duration. Therefore, there must be some other mechanism that determines the occurrence and duration of CC.

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