Fine progression features of return stroke luminosity at the bottom of rocket-triggered lightning channels

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Abstract. We have performed a study on the luminosity waveforms of 13 return strokes (RSs) in 4 rocket triggered lightning flashes recorded by a high-speed optical imaging system LAPOS5 with a time resolution of 35 ns and a spatial resolution of about 2 m. It was found that as the return strokes propagate upward over the bottom 10 m to 26 m of the lightning channels, which is above their initiation heights, on average the RSs optical waveforms decrease their peaks by 41%, lengthen their 20-90% rise times and 100-80% decay times, and change the relative times of the fastest rising points by 0.38 μs, 0.51 μs, and 0.15 μs. We have also estimated the propagation speeds for all the return strokes by using their 20% peak light intensity points and fastest rising points as reference points for time difference measurements, respectively. It was found that the average RS speed obtained with the 20% peak light intensity points (1.11×10^8 m/s) is about twice that obtained with the fastest rising points (0.67×10^8 m/s). In addition, we found that for different RSs in an individual lightning flash, the RS with faster propagation speed tends to have a less distorted optical waveform at the higher height.

Key words: Lightning, return stroke, rocket-triggered lightning

1. Introduction

Being the brightest part of a downward cloud-to-ground lightning flash outside the cloud, the return stroke (RS) is one of the most optically observed and studied lightning discharge processes. Based on the observations made using a Boys camera, Schonland et al. (1935) for the first time reported that the luminosity intensity of subsequent return strokes decreased from the lightning channel base upwards. Based on observations made by using a streak camera with a 1.0 μs time resolution and a 4 m spatial resolution, Jordan and Uman (1983) found that for seven subsequent RSs in natural lightning, their initial light peak amplitudes decreased exponentially with height, and their initial light 20-80% rise time increased by an additional 1 to 2 μs by the time the RS reached the cloud base. Based on the results of Jordan and Uman (1983), Master et al. (1981) improved Lin’s RS model (Lin et al., 1980) by introducing an exponential decay term to the breakdown pulse current. Wang et al. (2004) studied the luminosity profiles of four leader/RS sequences in a natural lightning flash observed with a digital imaging system named ALPS (Automatic
Lightning Progressing Feature Observation System) with a 0.1 μs time resolution and a 25 m spatial resolution. They found that the pulse–peak light intensity decreased linearly with height and the 10-90% rise time increased linearly with height along the bottom 210 m of the RS channels. Using a high-speed optical imaging system called LAPOS (Lightning Attachment Process Observation System) with the spatial resolution ranging from 9.5 m to 48.6 m, Tsukamoto et al. (2017) observed the RS propagation characteristics for both rocket-triggered lightning and natural lightning. They found that the changes of the light intensity and the 10-90% rise time versus height are much faster in rocket-triggered lightning flashes than those in natural lightning flashes. For the 22 RSs in rocket-triggered lightning, the peak light intensity and the 10-90% rise time at 40 m above the return stroke initiation point were about half and twice, respectively, of those at the initiation point.

However, one should note that concerning the return stroke process at the very bottom of the lightning channel, one of the least understood and most poorly documented parts of a return stroke, all previous observations are still not sufficient in terms of either time resolution or spatial resolution. For this, we have upgraded the LAPOS used by Tsukamoto et al. (2017) and performed new observations by focusing on the very bottom of the channel. With the new observation of data in this paper, we show more detailed features of the height profiles of the peak light intensity, the 20-90% rise time, the 100-80% decay time, and the relative time of fastest rising points of return stroke luminosity waveform from 10 m to 26 m above the strike point, the tip of a lightning rod. These height profiles allow us to analyze, for the first time, the correlation between the change ratio of the rise time and the change ratio of other parameters as well as the RS speed at the very bottom of the lightning channel. The change ratio of a parameter is defined as the ratio of the parameter values at two different heights (about 12 m and 25 m above the tip of lightning rod in this study).

2. Instrumentation and Data

As described in detail by Wang et al. (2017) and Huang et al. (2019), LAPOS 5 consists of a camera body, a 108×16 optical fiber array, multiple photodiodes and their amplifiers, and two digital storage oscilloscopes. Each line of the fiber array corresponds to one observation segment of LAPOS5, and can individually guide the light from a corresponding section of lightning channel to photodiodes. Compared to previous versions of LAPOSs (Wang et al., 2013), in LAPOS5, the light from a given height of lightning channel is split into two portions (90% and 5%) and separately guided into two photodiodes with different sensitivities, resulting in a larger dynamic range. Then, the output of photodiodes is recorded at the sampling rate of 100 MHz with two Yokogawa Scope DL850 oscilloscopes, resulting in a higher time resolution. During the summer of 2016, LAPOS 5 was set up at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida at a distance of 205 m from the rocket launcher used for artificially triggering lightning. The detailed layout of the launcher and the optical room for housing LAPOS5 can be found in Figure 1 of the paper by Carvalho et al. (2014). LAPOS5 was mounted with a 50 mm lens, resulting in a spatial resolution of about 2 m.
for the rocket triggered lightning flashes. With 14 observation segments of LAPOS5 above the lightning rod tip, the resultant vertical observation range was from the lightning rod tip to about 26 m above it.

A total of 16 return strokes in 4 rocket triggered lightning flashes recorded by LAPOS5 during the summer of 2016 are available for study. However, since 3 out of 16 strokes saturated a few LAPOS5 photodiodes, in this paper only 13 strokes are studied in detail. Table 1 gives the basic information of the 13 RSs, including the speeds, the peak currents and the time intervals from their preceding RSs. The peak currents were reported by the National Lightning Detection Network (NLDN). The $P_{20\%}$-RS-speed is determined with the time difference of 20% peak light intensity points as described by Zhou et al. (2019). The FR-RS-speed is determined with the time difference of the fastest rising points. As shown by Wang et al. (2014), return strokes usually have different luminosity height profiles above and below the return stroke initiation height. In order to avoid confusion, we limit our study on the height profile of each parameter over a vertical height range of about 10 m to 26 m above the strike point, a lightning rod, which is above the return stroke ignition heights determined using the onsets of RS waveforms for all the 13 strokes.

Table 1. Data list

| Flash No. | Time of the first RS | RS No. | Time interval (ms) | $P_{20\%}$-RS-speed ($10^8$ms$^{-1}$) | FR-RS-speed ($10^8$ms$^{-1}$) | RS peak current (kA) |
|-----------|----------------------|--------|-------------------|-------------------------------------|-----------------------------|-----------------------|
| 1         | 21:25:59 30/07/2016  | 1_1    | 54                | 0.82                                | 0.6                         | -14                   |
|           |                      | 1_2    | 149               | 1.46                                | 1.11                        | -14                   |
|           |                      | 1_3    | 234               | 0.98                                | 0.74                        |                       |
| 2         | 21:28:37 01/08/2016 | 2_4    | 108               | 1.05                                | 0.61                        | -8                    |
|           |                      | 2_5    | 128               | 0.93                                | 0.50                        | -4                    |
|           |                      | 2_6    | 135               | 0.97                                | 0.52                        | -4                    |
| 3         | 21:36:46 01/08/2016 | 3_1    | 120               | 1.05                                | 0.71                        | -6                    |
|           |                      | 3_2    | 120               | 1.75                                | 1.06                        | -4                    |
| 4         | 21:39:27 13/08/2016 | 4_1    | 46                | 1.98                                | 0.82                        | -22                   |
|           |                      | 4_2    | 150               | 0.67                                | 0.34                        | -6                    |
|           |                      | 4_3    | 280               | 0.59                                | 0.40                        | -10                   |
| Total /Average |        | 4      | 13                | 1.11                                | 0.67                        |                       |
3. Results

3.1 Example waveform

As an example, the light intensity waveform of RS No.1_1 at about 11.5 m above the lightning rod is shown in Figure 1 with a solid black line. On this line, the waveform peak is denoted with P; the points corresponding to 20% and 90% peak in the rise portion are denoted with A and B, respectively; the point corresponding to 80% peak in the decay portion is denoted with C. In order to better characterize such light intensity waveform, its time differential (dL/dt) is also shown in Figure 1 with a dotted black line. Point f on the dotted black line denotes the peak of dL/dt and its corresponding point on the light intensity waveform is denoted with F, representing the fastest rising point. The light intensity and time of each point is referred to as “L_x” and “T_x”, where “x” represents the label of each point. With these points, we have defined four parameters to characterize the RS optical waveform. Saturated waveforms, if any, are excluded in the following results.

Figure 1. Light intensity (solid black line) and time derivative (dotted black line) waveforms of RS No.1_1 at about 11.5 m above the lightning rod. P, F indicate the peak and the fastest rising point, respectively. A, B, and C indicate the points for 20% peak, 90% peak in the rise stage, and 80% peak in the decay stage, respectively. Point f denotes the peak of the time derivative waveform. The light intensity and the time at these points are denoted by L and T with the corresponding subscripts, respectively.
3.2 Height profiles of parameters

In this section, we present the height profiles of four parameters: the peak light intensity, the 20-90% rise time, the 100-80% decay time, and the relative time at the fastest rising point ($T_F$). For the light intensity, based on the assumption that the return stroke light intensity is relatively constant along height 30 μs after its initial peak (Jordan and Uman, 1983), we have normalized the light intensities of different observation sections in relative unit. In order to illustrate how fast the lightning channel establishes its luminosity, we have measured the waveform rise time with the time difference between two points at the initial rising stage. Due to the fact that the leader light intensity is over 10% of the RS peak light intensity for some RSs, the rise time in this study was measured from the time at 20% to 90% of the peak light intensity for each RS. Similarly, we use the 100-80% decay time measured with the time difference between point C and P to illustrate how fast the lightning channel decays its luminosity during the initial decay stage. Finally, we have measured the relative time at the fastest rising point ($T_F$) of each waveform. Using the time difference at these points and the corresponding height difference, we have obtained the return stroke propagation speed named FR-RS-speed in table 1.

3.2.1 Peak light intensity

Figure 2 shows the height profiles of peak light intensities for the 13 RSs in different colors. RSs in the same lightning flash are marked by the same shape. The peak light intensity ranges from 0.94 to 12.83 in relative unit with an average value of 4.18. As shown in Figure 2, although there are some irregular variations, all the RSs tend to have a smaller peak light intensity at the higher height. The red dots and black line show the

![Figure 2](image-url)
height profile of the average peak light intensity of all the RSs. The change ratio of average peak light intensity at 25 m and 10 m is about 0.6. Tsukamoto et al. (2017) reported that the light intensity at about 40 m height is about half of that at 0 m for RSs recorded by LAPOS3. Considering the different observation fields, the light intensity attenuation in this study appeared faster than that reported by Tsukamoto et al. (2017). For each of the RSs, the change ratios of peak light intensity at 25 m and 10 m are also calculated, and the corresponding results are shown in section 3.3.

3.2.2 20-90% Rise time

The 20-90% rise time versus height profiles for the 13 RSs are shown in Figure 3 in different colors. Similarly, RSs in the same lightning flash are marked by the same shape. The 20-90% rise time ranges from 0.22 μs to 0.85 μs with an average value of 0.54 μs. As shown in Figure 3, although there are some irregular variations, all the RSs tend to have a longer rise time at the higher height. The red dots and black line show the height profile of the average rise time of all the RSs. The average rise time at 25 m is about 2 times longer than that at 10 m. Tsukamoto et al. (2017) reported that the rise time at about 40 m height is about twice of that at 0 m for RSs recorded by LAPOS3. However, the increase of the rise time at the higher height in this study appeared faster than that reported by Tsukamoto et al. (2017) if the difference between two observation fields is taken into consideration. Also, we have calculated the change ratio of rise time at 25 m and 10 m for each RS, and the corresponding results are shown in section 3.3.

3.2.3 100-80% Decay time

The 100-80% decay time versus height profiles for the 13 RSs in different colors
are shown in Figure 4. Repeatedly, RSs in the same lightning flash are marked by the same shape. The 100-80% decay time ranges from 0.48 μs to 1.64 μs with an average value of 0.96 μs. As shown in Figure 4, all the RSs tend to have a longer 100-80% decay time at the higher height except for some irregular variations. The height profile of the average decay time of all the RSs is shown with red dots and a black broken line. We can see that the attenuation of light intensity at the higher height is slower than that at the lower height. The change ratio of the average 100-80% decay time at 25 m and 10 m is about 1.8. The change ratios of 100-80% decay time for each RS have also been calculated, and the corresponding results are also shown in section 3.3.

Figure 4. Scatter plots of the 100-80% decay time versus height for 13 RSs with different colors for different strokes. RSs in same lightning flash are marked with same shape.

3.2.4 The relative time of the fastest rising point (T_F)

Similar to the parameters described above, the relative time at point F (T_F) versus height profiles for 13 RSs are shown in Figure 5 in different colors. RSs in the same lightning flash are marked by the same shape. The red dots and black broken line show the height profile of the average value of T_F for all the RSs. For each RS, T_F at about 10 m is set to a common time 0. From Figure 5, we can see that for three return strokes of the second flash, the minimum value of T_F appears at about 13 m, indicating that the fastest changing process appears earlier at this height. As described above, the return stroke propagation speed measured with these fastest rising points are named as FR-RS-speed in Table 1. From the height of about 12 m to 25 m, the average FR-RS-speed of each RS is $0.6 \times 10^8$ m/s, $1.13 \times 10^8$ m/s, $0.97 \times 10^8$ m/s, $0.88 \times 10^8$ m/s, $0.62 \times 10^8$ m/s, $0.51 \times 10^8$ m/s, $0.54 \times 10^8$ m/s, $0.72 \times 10^8$ m/s, $1.06 \times 10^8$ m/s, $0.86 \times 10^8$ m/s, $0.37 \times 10^8$ m/s, $0.49 \times 10^8$ m/s, and $0.4 \times 10^8$ m/s, respectively. The average FR-RS-speed is about $0.7 \times 10^8$ m/s, and is
smaller than the $P_{20\%}$-RS-speed as shown in Table 1. For three return strokes of the second flash, the downward FR-RS-speed from about 13 m to 10 m is $0.25 \times 10^8$ m/s, $0.4 \times 10^8$ m/s and $0.28 \times 10^8$ m/s, respectively. The downward FR-RS-speed seems to be smaller than the upward FR-RS-speed. The correlation between the change ratio of rise time and the FR-RS-speed as well as the correlation between the change ratio of rise time and the $P_{20\%}$-RS-speed is shown in section 3.4.

3.3 Correlation between the change ratio of rise time and the change ratio of other parameters

The change ratio of a parameter at two heights shows how much the parameter has changed over the height range. For the parameter that increases with increasing height, the change ratio value is larger than 1, and a larger value represents a larger change of the parameter. On the contrary, for the parameter that decays with increasing height, the change ratio value is smaller than 1, and a smaller value represents a larger change of the parameter.

A scatter plot for the change ratio of 20-90% rise time versus the change ratio of peak light intensity for the 13 RSs is shown in Figure 6 (a). For the RSs in each flash, we have performed the linear regression analysis. The linear regression lines as well as the regression parameters are also given in Figure 6 (a). For all the four flashes, the coefficient of determination is over 0.94. Such relationship indicates that for the RSs in a lightning flash, the larger increase of the rise time is linearly related with the larger decay of the peak light intensity. A scatter plot for the change ratio of 20-90% rise time versus the change ratio of 100-80% decay time for the 13 RSs is shown in Figure 6 (b). Furthermore, we have performed the linear regression analysis for the RSs in each flash and the results
are also given in Figure 6 (b). For all the four flashes, the coefficient of determination is over 0.9. Such relationship indicates that for the RSs in a lightning flash, the larger increase of the rise time is linearly related with the larger change of the decay time.

3.4 Correlation between the change ratio of rise time and propagation speeds

As described above, we have determined the $P_{20\%}$-RS-speed with the 20% peak method, and determined FR-RS-speed with the time difference of fastest rising points. The scatter plots of the change ratio of 20-90% rise time versus $P_{20\%}$-RS-speed, and the change ratio of 20-90% rise time versus FR-RS-speed for different strokes in the four flashes are shown in Figure 7 (a) and (b), respectively. Similarly, the linear regression analysis has been performed for the RSs of each flash in both plots. The linear regression lines as well as the regression parameters are also given in Figure 7. As shown in Figure 7 (a), for each flash, the larger change ratio of rise time tends to be related with a smaller $P_{20\%}$-RS-speed, and all the coefficient of determination is over 0.88. As shown in Figure 7 (b), for each flash, the larger change ratio of rise time tends to be related with a smaller FR-RS-speed, and all the coefficient of determination is over 0.91. It is interesting to note that although the $P_{20\%}$-RS-speed and FR-RS-speed are determined with different methods and FR-RS-speed is smaller than $P_{20\%}$-RS-speed, for each flash, the linear relationship exists between the larger change ratio of rise time with both smaller $P_{20\%}$-RS-speed and smaller FR-RS-speed. Moreover, in both Figures 6 and 7, different flashes apparently exhibit different linear relationships. Since raining and window glass cloudy could affect the sensitivity of LAPOS5 in our experiment setup, the different linear relationships may just simply reflect that the 4 flashes were recorded under different environments.
4. Discussion

In order to illustrate the attenuation degree of RS optical waveforms, Wang et al. (2004) and Tsukamoto et al. (2017) calculated the attenuation coefficients of light intensity and rise time for RSs. Due to the different spatial resolutions and vertical observation ranges for rocket triggered lightning and natural lightning in Tsukamoto et al. (2017), the effect of height difference was eliminated through dividing by the height difference when calculating the attenuation coefficients. Given the fact that all the RSs in this study were observed with the same spatial resolution and vertical observation range, we use the change ratio, instead of using the attenuation coefficients, to illustrate how much the parameter has changed. Compared to the attenuation coefficients, the change ratio is easier to calculate and can show more directly the change of a parameter. From Table 3 in the paper by Tsukamoto et al. (2017), it seems that the absolute values of attenuation coefficients of the light intensity are positively related with that of the rise time for different lightning types. Unfortunately, the further analysis considering this relationship was not given by them. In this study, with the higher time and spatial resolution of LAPOS5, we found that the parameter change ratio is different even for different RSs in rocket triggered lightning flashes. Furthermore, we have analyzed the correlation among the change ratio of different parameters and RS speeds. As shown in Figure 6 (a) and Figure 7 (a), for the first time, we found that linear relationships exist between both the change ratio of the rise time versus the change ratio of the peak light intensity and the change ratio of the rise time versus the P20% RS-speed for RSs within the same flash. Tsukamoto et al. (2017) suggested that the attenuation coefficients are related with the conductivity of the return stroke channel. Based on that, they inferred that the channel conductivity is different for different lightning types. Similarly, by combining the
correlation results in this study, it can be inferred that the channel conductivity is different for different RSs in rocket triggered lightning flashes. Return strokes should propagate much easier along a channel with higher conductivity, and thus exhibit faster propagation speeds, slower change of the rise time and light intensity.

For the RS decay stage, Wang et al. (2008) suggested that the cumulative effect of some latter waves primarily forms the decay part of the RS waveform. As shown in their Figure 5 \((t=t_2)\), these latter waves are produced in neutralizing the space charge in the leader corona sheath and in the thundercloud. Given that these waves propagate to the return stroke channel core first and then down to the ground, and that the luminosity will attenuate during the propagation, the luminosity produced by these waves should be brighter at the higher height. That is, the RS waveform is expected to decay more slowly at the higher height due to the cumulative effect of latter waves. As shown in Figure 4, all the RSs in this study tend to have a longer 100–80% decay time at the higher height. It appears that our results support the cumulative effect assumption made by Wang et al. (2008). As we discussed above, RS waves propagating along channels with less conductivity could suffer larger attenuation in their light intensities. Similarly, for the latter waves that propagate along the channel with less conductivity, their light intensity attenuations will be bigger, and effectively cause a larger change ratio of the decay time. This inference is consistent with that the change ratio of the decay time is linearly related with the change ratio of rise time shown in Figure 6 (b).

Olsen et al. (2004) and Zhou et al. (2019) estimated the RS speed with various reference points. In this study, we have estimated the RS speed with two methods, one with 20% peak point and another with fastest rise point. The average RS speed estimated with 20% peak point in this study \((1.1 \times 10^8 \text{ m/s over 10 m to 25 m})\) is found to be slower than that reported by Olsen et al. (2004) \((1.24 \times 10^8 \text{ m/s over 7 m to 63 m})\), but faster than that reported by Zhou et al. (2019) \((0.87 \times 10^8 \text{ m/s over 26 m to 35.7 m})\). The average FR-RS-speed reported by Olsen et al. (2004) was 0.99 \times 10^8 \text{ m/s} \ (over 7 m to 170 m), which is faster than the 0.68 \times 10^8 \text{ m/s} \ (over 10 m to 25m) estimated in this study. In both studies, the average FR-RS-speed is found to be slower than the \(P_{20\%}-RS\)-speed. Although the average FR-RS-speed is about half of the \(P_{20\%}-RS\)-speed in this study, from Figure 7, it is interesting to note that the FR-RS-speed is also linearly related with the change ratio of rise time for each RS. Perhaps, this indicates that a return stroke may contain more than one wave even during its rising stage. For three RSs in the second flash, the fastest rising points appeared earlier at about 13 m even the RS initial heights measured with their leader luminosity waveforms are below 10 m. Apparently, this is a kind of contradiction. Perhaps this again indicates that a return stroke may contain more than one wave even during its rising stage. It seems that the fast transition waves in these three RSs occurred at a height higher than their slow front waves.

5. Conclusion

We presented the luminosity progression features of 13 RSs in 4 rocket triggered lightning flashes over the height range from 10 m to 26 m above the lightning termination point. The results show that as the return strokes propagate upward over this height
range, on average the RSs optical waveforms decrease their peaks by 41%, lengthen their 20-90% rise times and 100-80% decay times, and change the relative times of the fastest rising points by 0.38 μs, 0.51 μs, and 0.15 μs. The average RS speed obtained with the 20% peak light intensity points is about twice that obtained with the fastest rising points. For different RSs in the individual lightning flash, the RS with faster propagation speed tends to have a less distorted optical waveform at the higher height.

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