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Key Points:
- Positive leader velocities in hundreds of IC and −CG flashes are in a small range of 1 to 3 × 10^4 m/s
- Positive leader velocities in IC flashes tend to decrease as leader propagation altitudes increase
- Positive leaders in IC and −CG flashes propagate with a stable velocity

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Velocities of Positive Leaders in Intracloud and Negative Cloud-to-Ground Lightning Flashes

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Abstract We have performed a statistical study on velocities of positive leaders in 553 intracloud (IC) and 220 negative cloud-to-ground (−CG) flashes. It is found that velocities of positive leaders in IC and −CG flashes have very similar distributions, with the vast majority in the range of 1 to 3 × 10^4 m/s. Average velocities are 1.64 and 1.55 × 10^4 m/s, respectively, for positive leaders in IC and −CG flashes. Velocities of positive leaders in IC flashes show a clear negative correlation with initiation altitudes and leader propagation altitudes, similar to negative leaders in IC flashes. The negative correlation also exists for positive leaders in −CG flashes but is relatively weak. We also found that positive leaders in both IC and −CG flashes propagate with a stable velocity, contrary to downward positive leaders in +CG flashes and upward positive leaders in negative upward and triggered flashes, which were usually found to accelerate during propagations. These results suggest that positive leaders in IC and −CG flashes and those in +CG, upward and triggered flashes propagate with essentially different velocities. The differences and possible reasons are discussed.

Plain Language Summary Positive leaders in lightning flashes are much less well known than negative leaders. It has long been thought that positive leaders are an order of magnitude slower than negative leaders, but recent observations of positive leaders in positive cloud-to-ground (+CG), upward and rocket-triggered lightning suggest that positive leaders can be as fast as, or even faster than, negative leaders. In this study, velocities of positive leaders in 553 intracloud (IC) and 220 −CG flashes are analyzed, and it is found that positive leaders in IC and −CG flashes are indeed an order of magnitude slower than negative leaders. The results also suggest that positive leaders in IC and −CG flashes are different from those in +CG, upward and triggered flashes in many respects. The differences and possible reasons are discussed.

1. Introduction

It is widely accepted that natural lightning flashes start with bidirectional leaders with positive and negative ends propagating in opposite directions (Kasemir, 1960; Mazur & Ruhnke, 1993; Montanyà et al., 2015; Tran & Rakov, 2016; van der Velde & Montanyà, 2013). Compared with negative leaders, positive leaders are much less well studied. Unlike negative leaders in negative cloud-to-ground (−CG) flashes that ultimately propagate out of clouds and can be readily observed by high-speed video cameras, positive leaders in both −CG and IC flashes primarily develop inside clouds. Although positive leaders in positive cloud-to-ground (+CG) flashes propagate out of clouds before connecting to the ground, +CG flashes are usually much rarer than −CG and IC flashes and the chance of capturing them with high-speed video cameras is rather low (Kong et al., 2008; Saba et al., 2008; Wang & Takagi, 2011). Furthermore, although in-cloud negative leaders can be imaged by very high frequency and low-frequency (LF) lightning mapping systems (e.g., Lyu et al., 2016; Rison et al., 1999; Shao & Krehbiel, 1996; Wu et al., 2015), positive leaders usually radiate much more weakly in radio frequencies and are essentially masked by the radiation from the simultaneous negative leaders (Shao et al., 1999). As a result, most studies on positive leaders are based on observations of upward positive leaders from high structures (Lu et al., 2009; Shi et al., 2018; Wang et al., 2016; Wang & Takagi, 2012) or in rocket-triggered lightning (Biagi et al., 2009; Biagi et al., 2011; Edens et al., 2012; Hill et al., 2012; Jiang et al., 2013; Kito et al., 1985; Kotovsky et al., 2019; Sun et al., 2014; Yoshida et al., 2010).

A key property of positive leaders is the velocity of their propagations. It has long been thought that velocities of positive leaders are an order of magnitude smaller than those of negative leaders (Les Renardieres Group, 1977; Mazur et al., 1998; Williams, 2006). However, many recent observations of positive leaders in +CG lightning, upward lightning, and rocket-triggered lightning show that positive leaders can be as fast as, or even faster than, negative leaders (Chen et al., 2015; Saba et al., 2008; Wang & Takagi, 2011, 2012; Yoshida et al., 2010).

Relatively slow positive leaders (~2×10^4 m/s) have also been reported by a few studies but were observed in −CG and IC flashes (Lapierre et al., 2014; Proctor et al., 1988; Shao & Krehbiel, 1996; van der Velde & Montanyà, 2013). Their velocities were inferred by the extension of recoil leaders traversing positive leader channels. These results indicate that velocities of positive leaders in −CG and IC flashes may be fundamentally different from downward positive leaders in +CG and upward positive leaders in negative upward and rocket-triggered flashes. However, only a handful of cases have been reported in the literature, and it is not clear whether a systematic velocity difference exists for positive leaders in different types of lightning flashes. In this study, we will analyze positive leader velocities in 220 −CG flashes and 533 IC flashes. With such a large sample, we will be able to investigate the systematic differences between positive leader velocities in different types of lightning flashes as well as possible reasons for the differences.

For simplicity, downward positive leaders connecting to the ground in +CG flashes and initial upward positive leaders in negative upward and triggered lightning flashes will be referred to as "positive leaders in +CG, upward and triggered flashes" throughout this paper.

2. Data

Data in this study were obtained during the summer of 2017 in Gifu, Japan, with an LF lightning mapping system called Fast Antenna Lightning Mapping Array (FALMA). FALMA can reconstruct three-dimensional (3-D) structures of lightning flashes with great detail, and, with the help of electric field change waveforms recorded at multiple sites, allows us to unambiguously determine types of lightning discharges. More details and examples of lightning flashes imaged by FALMA can be found in Wu et al. (2018a).

During the summer of 2017, thousands of IC and −CG flashes were recorded. For the study of positive leaders, 966 IC flashes and 336 −CG flashes with clear positive leader channels were selected. A simple method described in section 3.1 was used to estimate overall velocities of positive leaders. For some lightning flashes, estimations with this method had relatively large errors and were excluded for the analysis. Ultimately, 533 IC flashes and 220 −CG flashes were used for the calculation.

As evidence for the discussion (section 5), overall velocities of downward positive leaders in +CG flashes are also briefly analyzed. As reported by Wu et al. (2018b), 46 +CG flashes were observed inside or near the network of the FALMA during the summer of 2017. Positive leader velocities were roughly estimated by dividing the 3-D distance by the time difference between the first source of a flash and the first return stroke. Only flashes with the horizontal distance between the first source and the first return stroke smaller than 5 km were selected. With this criterion, 27 out of 46 +CG flashes were selected for this calculation.

3. Methodology

3.1. Rough Estimation of Overall Velocities

Positive leaders in IC and −CG flashes usually cannot be directly detected due to their weak radiation in radio frequencies. However, as the positive leader develops, the so-called recoil leader (or K change, K process) repeatedly develops either at or close to the tip of the positive leader (e.g., Saba et al., 2008; Warner et al., 2012) back toward the origin of the flash and sometimes into the negative leader channel. These recoil leaders carry negative charges and have strong radiation and can be well resolved by the FALMA. From the initiation locations of recoil leaders, the development of positive leaders can be inferred.

Figure 1 shows the 3-D mapping result of an IC flash with the typical bilevel structure. The initiation point of this flash is shown as a triangle, which connects negative leader channels shown in blue and positive leader channels shown in red. Similarly, Figure 2 shows the 3-D mapping result of a −CG flash. This flash had 11 return strokes with three different terminations. Positive leaders in both IC and −CG flashes mainly propagate horizontally in the main negative charge region.

From these two examples, we can see that positive leaders in IC and −CG flashes have many branches, but most of the branches do not show well-defined channel structures; this is due to the fact that the radiation sources are from recoil leaders which occur intermittently. Therefore, it would be impractical to identify each channel and

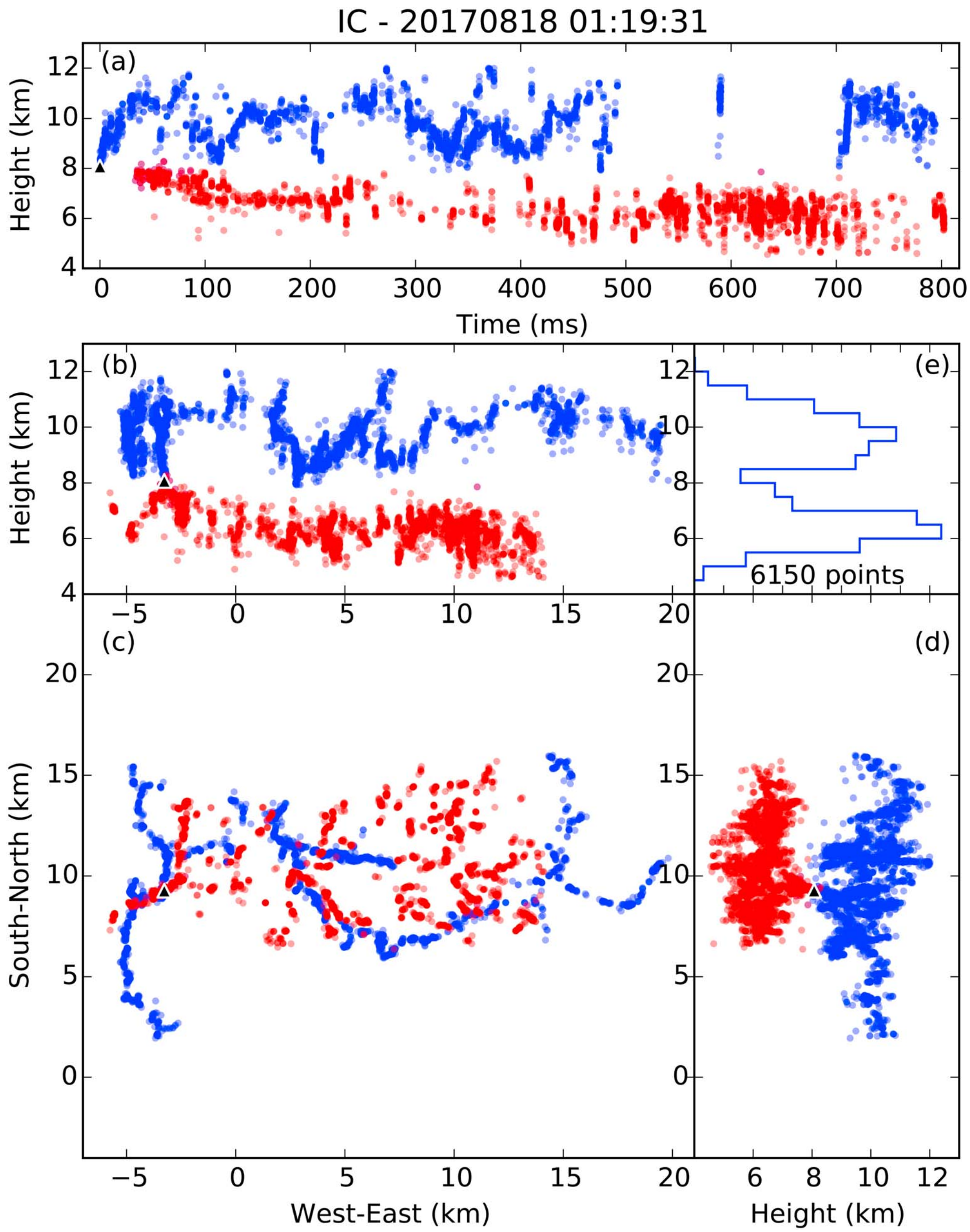

Figure 1. The 3-D mapping result of an intracloud flash. (a) Height-time view. (b) Height-distance (from west to east) view. (c) Plan view. (d) Distance (from south to north)-height view. (e) Source distribution along the height. The triangle represents the first source of this flash. Blue dots represent negative leaders and red dots represent positive leaders.

calculate the 3-D velocity for each branch. In this study, we use a simple method similar to that used by van der Velde and Montanyà (2013) and Schultz et al. (2018), who estimated positive and negative leader velocities with the Lightning Mapping Array data, to roughly estimate the overall velocity of positive leaders. All sources of positive leader channels (red sources in Figures 1 and 2) are selected and the 3-D distance and time difference between each source and the first source (the triangles in Figures 1 and 2) are calculated. The distance-time relations for positive leaders in the two flashes in Figures 1 and 2 are shown in Figure 3.

For the selected positive leader sources (red dots in Figure 3), an automated process is developed to estimate the leader velocity. First, each flash is divided into multiple 20-ms windows, and in each window the positive leader source with the maximum distance from the origin is selected, shown as black and yellow dots in Figure 3. Second, from these black and yellow dots, possible outliers (yellow dots) are identified and excluded. These outliers are

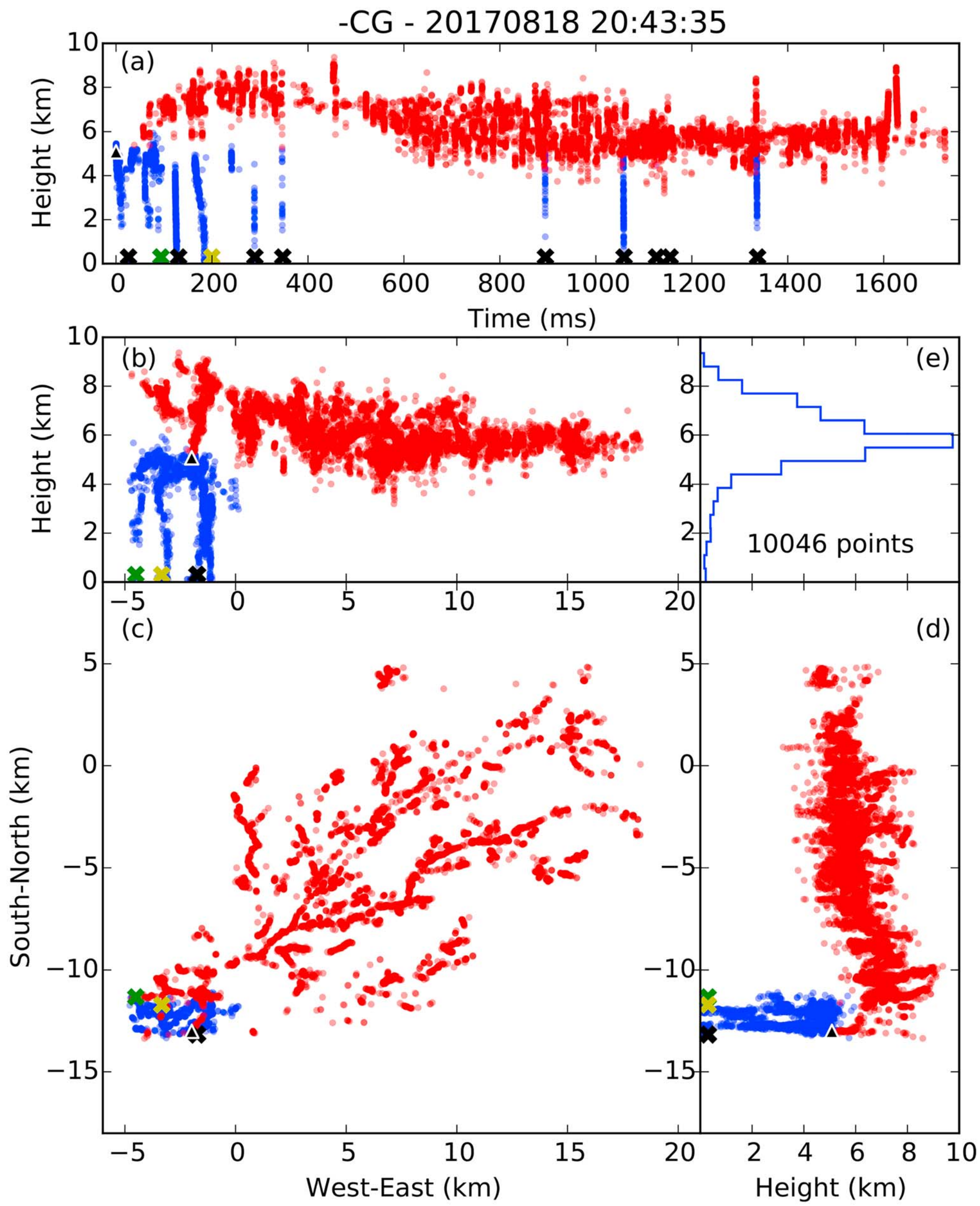

Figure 2. The same as Figure 1 but for a negative cloud-to-ground (−CG) flash. Cross signs represent return strokes (different colors indicate different striking points).

identified as those points with distances smaller than the previous two points or larger than the following two points. Finally, for the remaining points with maximum distances (black dots), a linear regression is made and the slope is determined as the overall velocity. For the IC flash in Figure 1 and the −CG flash in Figure 2, overall velocities of positive leaders are estimated to be 2.4 and 1.5×10^4 m/s, respectively.

This method is relatively accurate for positive leaders mainly developing outward in the radial direction but inaccurate for those developing in the tangential direction. Therefore, only lightning flashes with positive leaders mainly developing in the radial direction are selected for the estimation of velocities. As described in section 2, from 966 IC flashes and 336 −CG flashes with relatively good location results, 533 IC flashes and 220 −CG flashes have been selected for this analysis.

3.2. Estimation of 3-D Velocities

For some positive leader branches that are well located, we can estimate 3-D velocities in a more accurate way. Figure 4a shows the plan view of positive leader sources in the −CG flash in Figure 2. A branch

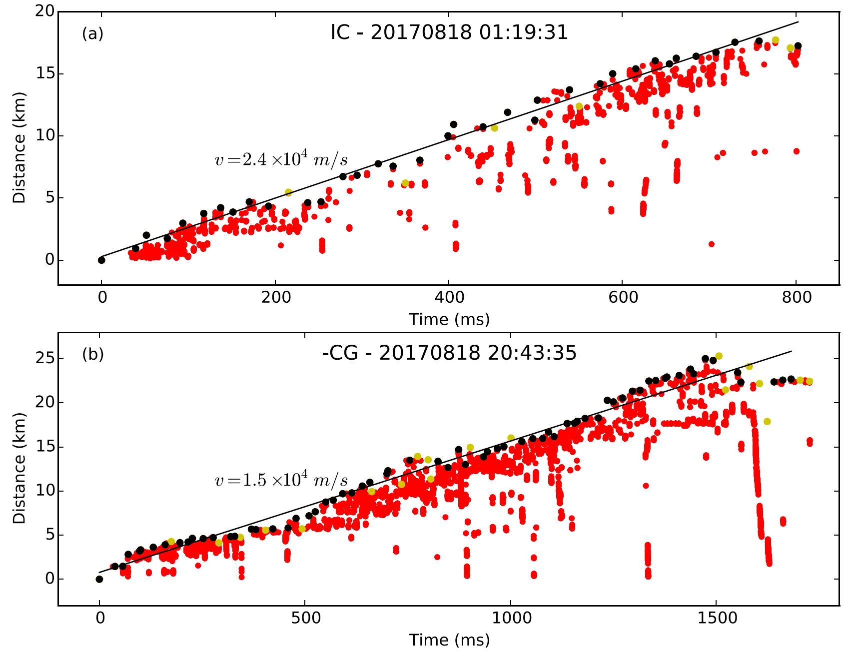

Figure 3. Estimation of positive leader velocities for (a) the intracloud (IC) flash in Figure 1 and (b) the negative cloud-to-ground (−CG) flash in Figure 2. Red dots are positive leader sources. Black and yellow dots are sources with the maximum distance in 20-ms windows. Yellow dots are determined as outliers. Black lines are the linear regression lines for black dots. Slopes of the regression lines are the estimated velocities. See section 3.1 for more details.

whose structure can be clearly recognized are shown in red. In order to divide the channel into multiple linear segments, four nodes labeled as “1” to “4” are chosen and are shown as blue circles in Figure 4a. Channel segments between successive nodes can be roughly considered as straight lines. Distances of the branch sources (red dots) are calculated relative to these four nodes. Specifically, sources between Nodes 1 and 2 are calculated relative to the location of Node 1, and sources between Nodes 2 and 3 are calculated relative to the location of Node 2, with the addition of the distance between Nodes 1 and 2, and so on. Finally, sources after the node 4 are calculated relative to the location of Node 4, with the addition of the cumulative distance from Node 1 to Node 4. In this way, influences from the variation of propagation directions can be minimized. Source altitudes are also considered in these calculations, so the estimated results are 3-D velocities. Further, time differences are calculated relative to the earliest source between Nodes 1 and 2.

Figure 4b shows the distance-time scatterplot of the selected sources in Figure 4a. The same automated process described in section 3.1 is used to identify the black dots, which indicate the general location of the positive leader tip. We can see that the black dots show a clear linear distance-time relationship, indicating that the positive leader does not show evident velocity variations during its propagation. The velocity is estimated to be 1.6×10^4 m/s, very close to the overall velocity of 1.5×10^4 m/s estimated in section 3.1. Positive leaders in this flash mainly propagated in the radial direction, so it is expected that the result estimated using the simple method described in section 3.1 is similar to the 3-D result estimated here.

4. Results

4.1. Distributions of Positive Leader Velocities

With the method described in section 3.1, velocities of positive leaders in 552 IC flashes and 220 −CG flashes are calculated, and their distributions are shown in Figure 5. Positive leader velocities in IC and −CG flashes show very similar distributions, both having peaks around 1.5×10^4 m/s. Velocities for positive leaders in IC flashes have an average value of 1.64×10^4 m/s with a maximum of 3.2×10^4 m/s and a minimum of 1.0×10^4 m/s, and velocities for positive leaders in −CG flashes have an average value of 1.55×10^4 m/s with a maximum of 3.0×10^4 m/s and a minimum of 0.92×10^4 m/s. An overwhelming majority (532 of 533 IC flashes and 218 of 220

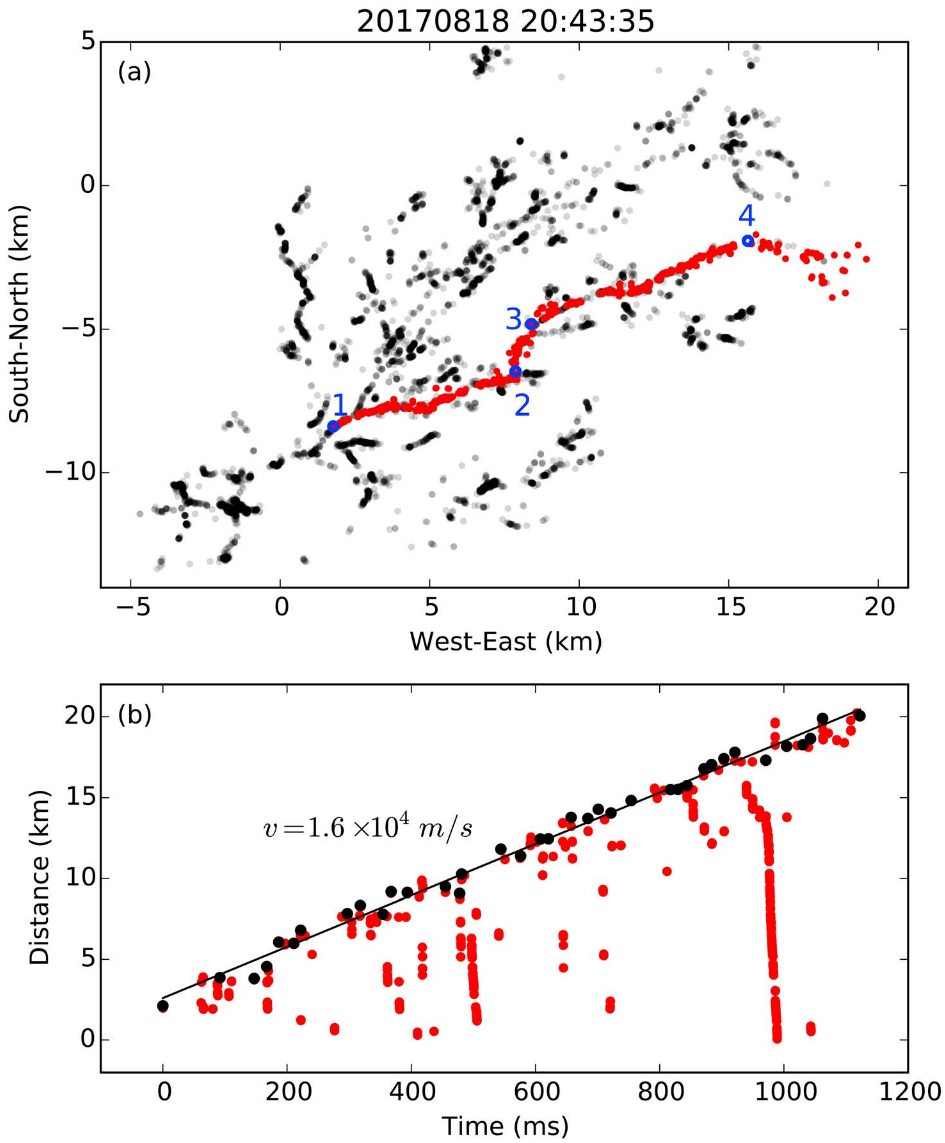

Figure 4. Illustration of the method to calculate the 3-D velocity of a positive leader branch in the negative cloud-to-ground flash in Figure 2. (a) Plan view of positive leader sources. Red dots represent the selected positive leader branch. Four blue circles represent four nodes to divide the channel into four segments. (b) Distance-time view of the selected sources (red dots in Figure 4a). The same method in Figure 3 is used to determine the linear regression line and estimate the velocity. See section 3.2 for more details.

−CG flashes) is in the range of 1 to 3×10^4 m/s. Therefore, positive leaders in IC and −CG flashes are indeed one order of magnitude slower than negative leaders (Les Renardieres Group, 1977; Williams, 2006).

From the above results, it is interesting to note that the range of positive leader velocities in IC and −CG flashes is very small, from 0.92 to 3.2×10^4 m/s, the maximum being only about 3.5 times as large as the minimum. In contrast, Wu et al. (2015) reported that negative leader velocities in 662 IC flashes ranged from 0.5 to 17.8×10^5 m/s, the maximum being about 35 times as large as the minimum. Positive leader velocities in +CG, upward and triggered flashes seem to have even larger differences in different observations, large velocities being 2 orders of magnitude larger than small velocities (e.g., Edens et al., 2012; Saba et al., 2010; Wang & Takagi, 2011; Yoshida et al., 2010).

In spite of the very small range (0.92 to 3.2×10^4 m/s), previous reports of positive leader velocities of IC and −CG flashes in different regions all fall within this range (Lapierre et al., 2014; Shao & Krehbiel, 1996; van

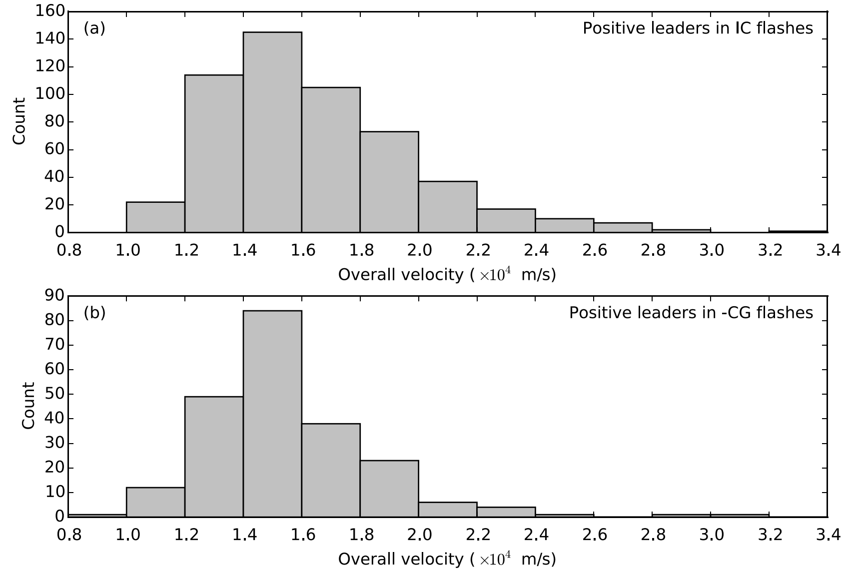

Figure 5. Distributions of positive leader velocities in (a) intracloud (IC) and (b) negative cloud-to-ground (−CG) flashes.

der Velde & Montanyà, 2013), indicating that velocities of positive leaders in IC and −CG flashes do not have large variations in different lightning flashes or different thunderstorms.

4.2. Relationship Between Positive Leader Velocity and Altitude

Wu et al. (2015) demonstrated that velocities of initial negative leaders in IC flashes decreased as initiation altitudes increased. Proctor (1997) also found that lightning flashes initiating at higher altitudes

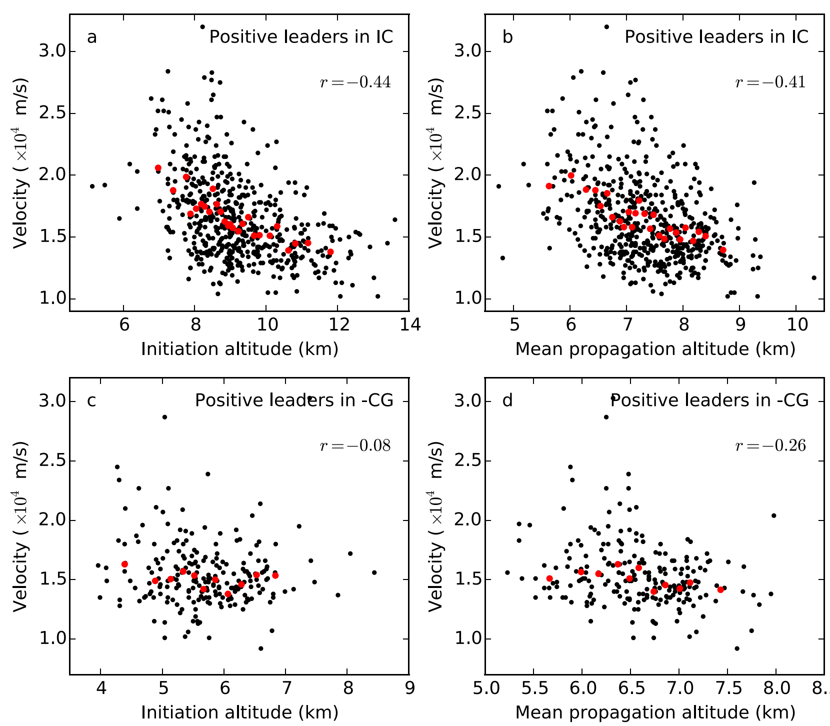

Figure 6. Relationships between positive leader velocities and initiation altitudes and mean propagation altitudes for (a and b) intracloud (IC) flashes and (c and d) negative cloud-to-ground (−CG) flashes. Red dots represent average velocities for every 20 consecutive black dots. Values of *r* represent correlation coefficients.

had relatively slow negative leaders. In this section, we will investigate whether positive leaders have the similar feature.

Velocities of all positive leaders in IC and −CG flashes calculated in section 4.1 are plotted against initiation altitudes of lightning flashes and mean propagation altitudes of positive leaders as shown in Figure 6. The value of r indicates the correlation coefficient between velocities and initiation altitudes or mean propagation altitudes. The initiation altitude is calculated as the altitude of the first source in a flash, assuming initial positive and negative leaders start from the same point. The mean propagation altitude is calculated as the median altitude of all positive leader sources in a flash. Further, average velocities for every 20 consecutive events are calculated and are shown as red dots in Figure 6.

From Figure 6, we can see that for positive leaders in IC flashes, velocities show a clear decreasing trend with increasing initiation altitudes and mean propagation altitudes. Correlation coefficients are −0.44 and −0.41, respectively, for initiation altitudes and mean propagation altitudes. This result is similar to the negative correlation between initiation altitudes and initial negative leader velocities in IC flashes (Wu et al., 2015).

For positive leaders in −CG flashes, no correlation can be recognized between velocities and initiation altitudes (the correlation coefficient is −0.08). However, a weak negative correlation exists between velocities and mean propagation altitudes (the correlation coefficient is −0.26). It seems that positive leader velocities in −CG flashes are also influenced by leader propagation altitudes but compared to positive leaders in IC flashes, other factors may have larger influences.

Edens et al. (2012) reported velocities in the range of 1 to 3×10^4 m/s for a positive leader in a triggered flash in New Mexico. They noted that positive leaders in triggered lightning appeared to propagate more slowly in New Mexico than in other regions, but the reason was not clear. It is possible that the negative correlation between positive leader velocity and the altitude is also applicable to triggered lightning, and the high altitude (3.2 km above sea level) of the lightning triggering facility in New Mexico contributed to the low velocity.

It should also be noted that although altitudes of positive leaders in −CG flashes are generally lower than those in IC flashes, velocities of positive leaders in −CG flashes are essentially the same as those in IC flashes. Therefore, positive leaders in IC and −CG flashes as a whole do not preserve the altitude-velocity correlation.

4.3. Velocity Variations During Leader Propagations

Many observations have shown that both downward positive leaders in +CG flashes and upward positive leaders in upward and rocket-triggered lightning flashes accelerate as they propagate (Biagi et al., 2011; Campos et al., 2014; Jiang et al., 2013; Kito et al., 1985; Kong et al., 2008, 2015; Saba et al., 2008, 2010; Wang & Takagi, 2011). In this section, we will investigate whether positive leaders in IC and −CG flashes have the similar behavior.

Overall velocities estimated by the method described in section 3.1 are influenced by propagation directions of leaders and cannot accurately indicate variations during leader propagations. Therefore, the method described in section 3.2 is used and 3-D velocities of positive leaders with clear channels in 10 IC flashes and 10 −CG flashes are calculated. Figures 7 and 8 show results for IC and −CG flashes, respectively. For each flash, the estimated 3-D velocity is shown above the regression line, with the overall velocity estimated using the method described in section 3.1 shown in parentheses, both in the unit of 10^4 m/s.

From Figures 7 and 8, it seems that although in some cases, the velocities show certain slight variations (Figures 7c, 7e, and 8i), in most cases, velocities of positive leaders in both IC and −CG flashes do not show evident variations as the leaders propagate. Previous studies of positive leader velocities in +CG, upward and triggered flashes usually reported large increases as leaders propagated. For example, Kong et al. (2008) showed that the velocity of a positive leader in a +CG flash increased from 0.1 to 3.8×10^5 m/s as it approached the ground. Biagi et al. (2011) reported that the velocity of an upward positive leader in a rocket-triggered lightning flash increased from 5.5×10^4 m/s between heights of 123 and 134 m to 2.1×10^5 m/s at a height of 350 m. Such large increases clearly do not exist in Figures 7 and 8. Propagation distances of the positive leaders shown in Figures 7 and 8 are generally larger than 10 km, longer than those

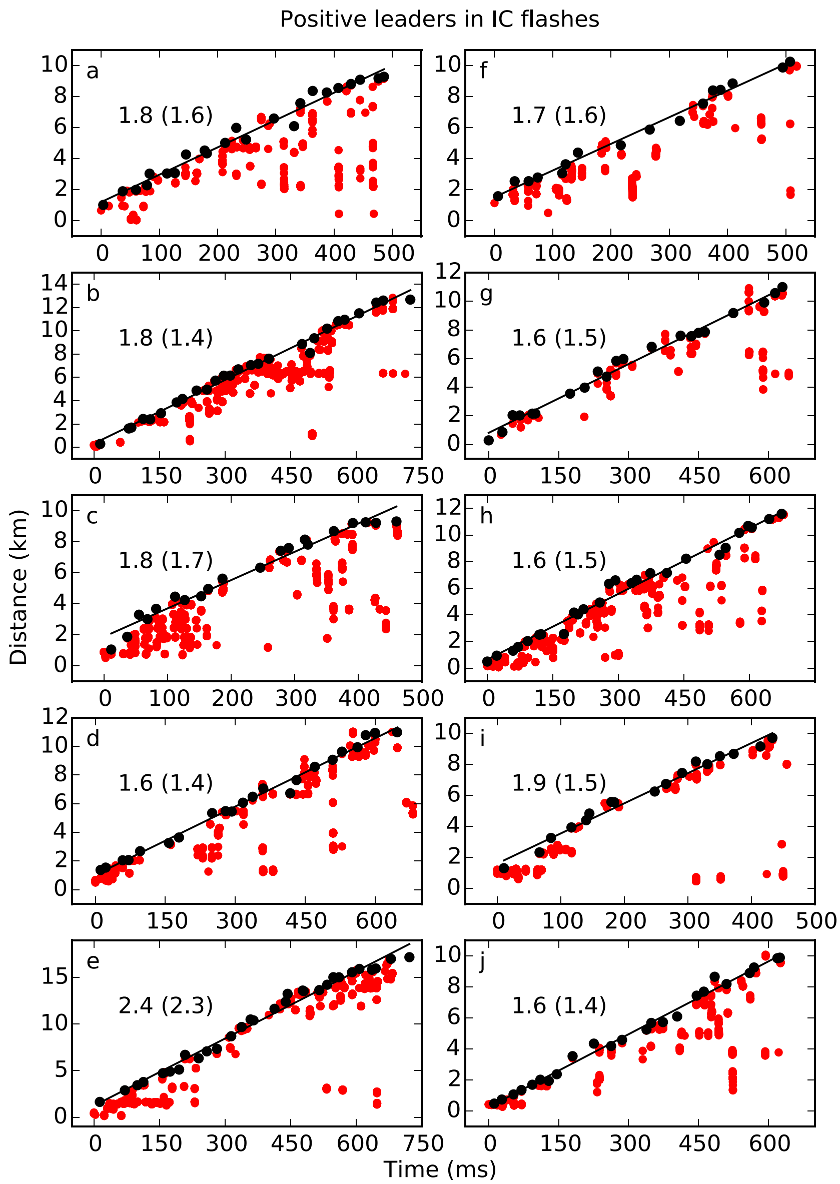

Figure 7. Velocity estimation in 3-D for positive leaders in 10 intracloud (IC) flashes. Numbers above regression lines indicate 3-D velocities ($\times 10^4$ m/s; section 3.2), and those in parentheses indicate overall velocities ($\times 10^4$ m/s; section 3.1).

observed in +CG, upward and triggered flashes, indicating that positive leaders in both IC and −CG flashes propagate with a stable velocity over a large distance.

These results also demonstrate that overall velocities estimated with the method described in section 3.1 do not have large differences with 3-D velocities. Most of the cases analyzed here have a difference smaller than 20%. The selection of positive leaders that mainly propagate in the radial direction accounts for this small difference (section 3.1).

5. Discussion

From the results of this study, we can see that there are several major differences between velocities of positive leaders in IC and −CG flashes and those in +CG, upward and triggered flashes. First, positive leaders in +CG, upward and triggered flashes are generally faster than those in IC and −CG flashes. Velocities of positive leaders in +CG, upward and triggered flashes are mainly above 3×10^4 m/s (Biagi et al., 2009, 2011; Hill et al., 2012; Kong et al., 2015; Saba et al., 2010; Wang & Takagi, 2011, 2012;

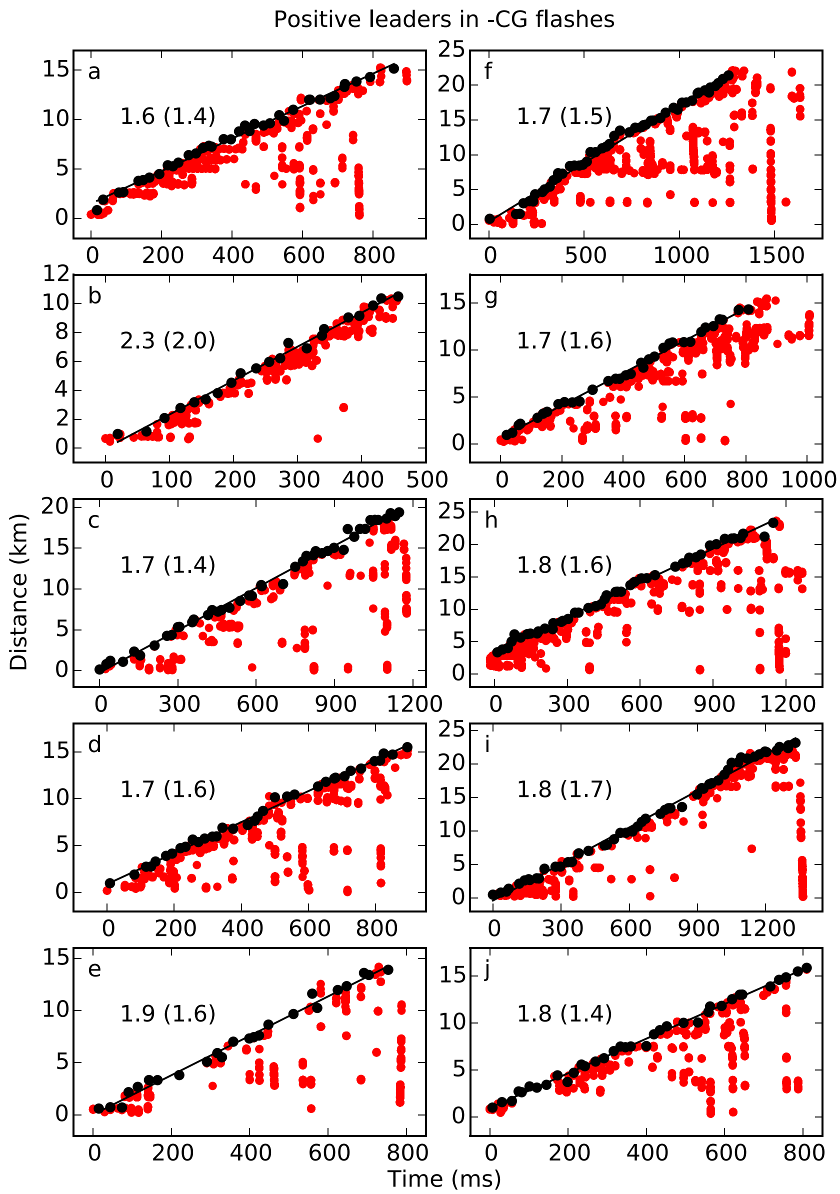

Figure 8. The same as Figure 7 but for 10 negative cloud-to-ground (−CG) flashes.

Yoshida et al., 2010), which is virtually the upper end of positive leader velocities in IC and −CG flashes. Second, positive leaders in +CG, upward and triggered flashes are frequently observed to accelerate during propagations (Biagi et al., 2011; Campos et al., 2014; Jiang et al., 2013; Kito et al., 1985; Kong et al., 2008, 2015; Saba et al., 2008, 2010; Wang & Takagi, 2011), while those in IC and −CG flashes do not show clear variations in velocity as they propagate. Third, velocities of positive leaders in +CG, upward and triggered flashes observed in different studies span a very wide range, from 10^4 to 10^6 m/s, but those in IC and −CG flashes concentrate in a small range of 1 to 3 × 10^4 m/s. We discuss the possible reasons for these differences in following sections.

5.1. Why Positive Leaders in +CG, Upward and Triggered Flashes Accelerate While Those in IC and −CG Flashes Do Not

Positive leaders in +CG, upward and triggered flashes reported in previous studies essentially propagated vertically between charge regions in thunderclouds and the ground or high objects on the ground (wire-trailing rockets in the case of triggered lightning) where the electric field-height profile is

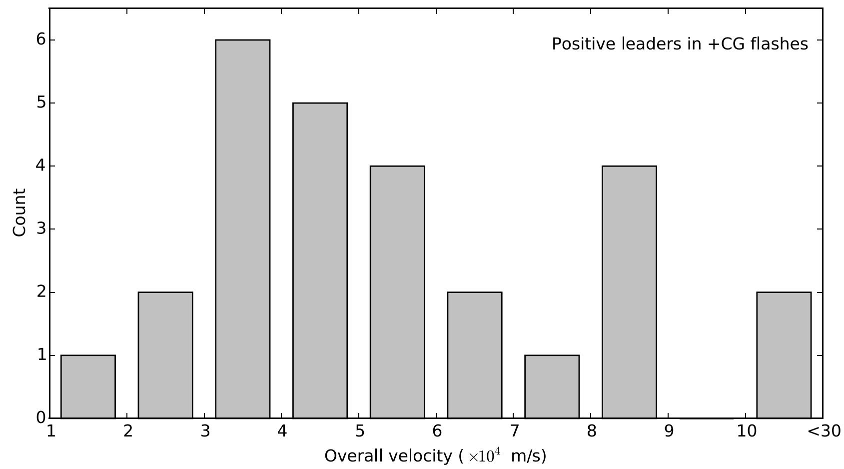

Figure 9. Distribution of positive leader velocities in positive cloud-to-ground (+CG) flashes.

strongly influenced by the effect of electrostatic induction of the ground and high objects. For example, in the case of positive leaders in +CG flashes, they propagate from charge regions in thunderclouds toward the ground, and as they approach the ground, the electric field between the tip of positive leaders and the ground increases, which may be the reason for increased velocities.

As for positive leaders in IC and −CG flashes, they propagate mainly horizontally inside negative charge regions. As charged particles are distributed approximately uniformly in the horizontal direction, the background electric field in the horizontal direction is not as significant as that in the vertical direction. Therefore, propagations of positive leaders in IC and −CG flashes are barely affected by the background electric field and the velocities are stable.

There have also been high-speed video observations of positive leaders propagating in largely horizontal directions near cloud bases, and unlike vertical positive leaders in +CG, upward and triggered flashes, these horizontal positive leaders seem to propagate with relatively stable velocities. For example, Saba et al. (2008) observed that one horizontal positive leader segment between altitudes of 2,200 and 2,700 m showed no increase in the velocity. Similar observations can also be found in Montanyà et al. (2015) and Yuan et al. (2019). These observations support the above explanation that the increase in velocity for positive leaders in +CG, upward and triggered flashes is due to the vertical propagation and approach to a virtual electrode.

5.2. Why Positive Leaders in +CG, Upward and Triggered Flashes Have Very Different Velocities in Different Observations While Those in IC and −CG Flashes Do Not

As discussed above, the background electric field in the horizontal direction is relatively weak in negative charge regions in which positive leaders of IC and −CG flashes propagate, so positive leaders of IC and −CG flashes observed in different studies essentially propagate in similar background electric fields. As a result, velocities of positive leaders in IC and −CG flashes have a very small range, even in different thunderstorms and different regions. On the other hand, the ambient electric field for positive leaders in +CG, upward and triggered flashes is influenced by the induction effect of the ground and high objects on the ground, with the height profile dependent on the altitude and shape of grounded objects, the topography, the charge amount in thunderclouds, the altitude of charge regions, and so on. As a result, positive leaders in +CG, upward and triggered flashes present significantly different velocities in different observations.

5.3. Why Positive Leaders in +CG, Upward and Triggered Flashes Are Generally Observed to be Faster Than Those in IC and −CG Flashes

The reasons for +CG flashes and upward and triggered flashes may be different. For positive leaders in +CG flashes, they were observed by high-speed video cameras when they had propagated out of thunderclouds and approached the ground, so the "average velocity" of positive leaders in +CG flashes reported by previous studies was the average velocity for approximately the final 2,000 m or less before the leaders connected to the ground (Campos et al., 2014; Saba et al., 2008; Wang & Takagi, 2011). Considering the observation that positive leaders in +CG flashes usually accelerate as they approach the ground (e.g., Biagi et al., 2011; Campos et al., 2014; Wang & Takagi, 2011), the initial velocity when the leaders are inside thunderclouds is likely much lower than the reported values on the order of 10^5 or even 10^6 m/s.

As described in section 2, overall velocities of positive leaders in 27 +CG flashes observed in the current study have also been calculated. These velocities were roughly estimated from the 3-D distance and the time difference between the first source of a +CG flash and the first return stroke. The distribution of velocities is shown in Figure 9. Only flashes with the horizontal distance between the first source and the first return stroke smaller than 5 km were selected for this calculation, so we believe these results are relatively accurate. From Figure 9 we can see that the majority of velocities are on the order of 10^4 m/s, and more than half are below 6×10^4 m/s. Initial velocities of positive leaders when they are inside thunderclouds should be lower than these values, and it is possible that they are actually similar to the velocities of positive leaders in IC and −CG flashes reported in this study.

High velocities of positive leaders in upward and triggered flashes are likely due to the existence of tall objects, which significantly increases the local electric field. According to Wang and Takagi (2012), initial velocities of positive leaders from a tower of 330 m above the sea level were about 1 to 2×10^6 m/s, while those from a tower of 145 m above the sea level were about 1 to 2×10^5 m/s, indicating the effect of high objects in increasing positive leader velocities.

6. Conclusions

Velocities of positive leaders in 533 IC flashes and 220 −CG flashes are analyzed. It is found that velocities of the majority of positive leaders in both IC and −CG flashes are in a small range of 1 to 3×10^4 m/s. Average velocities are very close, 1.64 and 1.55×10^4 m/s, respectively, for positive leaders in IC and −CG flashes. Velocities of positive leaders in IC and −CG flashes are generally lower than those in +CG, upward and triggered flashes reported in previous studies. It seems possible that positive leader velocities in IC and −CG flashes in different thunderstorms and different regions mostly fall in the small range of 1 to 3×10^4 m/s. It is also found that positive leaders in IC and −CG flashes propagate with a stable velocity, contrary to those in +CG, upward and triggered flashes, which were usually found to accelerate during propagations. Differences between positive leader velocities in IC and −CG flashes and those in +CG, upward and triggered flashes are likely due to different environments in which positive leaders propagate. Positive leaders in IC and −CG flashes mainly propagate horizontally in the main negative charge region while those in +CG, upward and triggered flashes mainly propagate vertically outside thunderstorms, and the different ambient electric field may be the primary reason for the different velocities.

Similar to negative leaders in IC flashes, positive leaders in IC flashes also tend to have smaller velocities at higher altitudes. The negative correlation between velocities and propagation altitudes also exists for positive leaders in −CG flashes but is relatively weak, suggesting that factors other than the altitude have larger influences on velocities of positive leaders in −CG flashes.

Acknowledgments
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