LIGHTNING FLASH LENGTHS DEDUCED FROM VHF RADIATION FOR A COLORADO THUNDERSTORM

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Abstract. Two different techniques are applied to measurements from a lightning VHF interferometer to estimate total channel lengths of lightning flashes in a thunderstorm that occurred in northeastern Colorado on 10 July 1996. The XY method derives total lengths based on the sum of elementary lengths between the locations of two successive VHF emission sources. The one-station method uses the characteristics and angular locations of the VHF radiation detected by the interferometer to differentiate between negative leaders and fast negative processes combined with simple relationships from the physics of lightning to deduce the channel lengths of these components for both intra-cloud and cloud-to-ground lightning flashes. The length estimates from the one-station method are thought to have uncertainties of a factor of 2 to 3 and for negative leaders are most likely underestimates of actual leader lengths. The XY method gave estimates of total flash lengths greater than the one-station method by a factor of 5 to 10. These overestimates are shown to be a result of inaccuracies and resulting scatter in the locations determined by the interferometer system for the VHF sources. The results from the XY method are considered upper limits. In spite of the difference in absolute values given by the two methods, variations in average total channel length per flash derived from the two totally independent methods show temporal similarity over the 4 ½ hour lifetime of the storm. This and the correspondence of the derived lengths with variations in CG and IC flash frequency during the storm suggest that the variations in flash length with time are real.

This storm produced over 5000 flashes with only 83 connecting to ground. The total component length of individual flashes retrieved from the one-station method varied from 0.02 to 474 km with an average value of 19 km. The sum of total channel lengths for all flash components for the 4 1/2 hour storm was estimated at 102,000 km. For flashes with duration >10 ms the length per flash was found to be related to the flash duration but with a lot of variation. The lightning channel lengths deduced from this work are used in a companion paper by *Skamarock et al*. [2002] to estimate NO_x (= NO + NO_2) produced by lightning in the 10 July 1996 storm.

1. Introduction

Thunderstorms vary widely over the globe and even regionally in terms of their size, severity and lifetimes. For example, much less lightning activity occurs in storms over the oceans than for storms over land. Likewise lightning activity within individual storms can show large variability during the lifetime of a storm. Electric field change measurements and more recently VHF lightning mappers have shown that flash rates of both cloud-to-ground (CG) and intra-cloud (IC) lightning and the ratio of IC to CG lightning can also vary widely. With the advent of VHF lightning mapping systems we are able to study the characteristics of individual flashes and also map the location traversed by flashes in great detail (e.g. *Proctor* [1981]; *Shao et al*., [1995]; *Shao and Krehbiel* [1996]; *Thomas et al.* [2001]). Additionally we have learned more about overall lightning characteristics in individual storms. For example, *Mazur et al*. [1984] has shown that during the stratiform decay phase of some storms individual flashes can exhibit large horizontal branches extending many tens of kilometers, while *Stanley et al*. [1996] have shown that flashes early in the lifetime of a storm tend to be mostly vertical.

VHF lightning mappers also give us the ability to study the characteristics and evolution of both IC and CG flashes over the lifetime of a storm, although few studies of this nature have been reported so far. In a recent study *Defer et al.* [2001] used measurements from the Office National D'Etude et de Recherches Aérospatiales (ONERA) VHF lightning interferometer to determine flash rates, ratios of IC to CG flashes and flash durations over the entire 4 1/2 hour lifetime of a storm which occurred in northeastern Colorado on 10 July 1996. In this paper we extend the results of *Defer et al*. to report a new technique that allows us to estimate the length of negative leaders and fast negative processes using the measurements from the ONERA VHF lightning mapper. Herein, we use the term fast negative processes to mean K events (sometimes called K changes or streamers), dart leaders, or recoil streamers. We then use this technique to investigate the length of negative leaders, fast processes, and individual flashes over the lifetime of the 10 July 1996 storm. In addition to providing additional information on lightning characteristics of this storm, part of the motivation for estimating flash lengths is to investigate the production of nitrogen oxides (NO_x) by lightning. Previous studies have used individual flashes or flash rates to study NO_x production by lightning. Given the large variability between individual flashes in terms of types, durations, currents and energies, we sought to use other properties of lightning to investigate NO_x production in the 10 July storm. In a companion paper by *Skamarock et al*. [2002] the channel length measurements from this paper are combined with measured NO_x values in the anvil and a cloud simulation of the storm to examine NO_x production per flash and per unit lightning channel length.

2. The ONERA VHF interferometric system

During the summer of 1996 the Stratosphere-Troposphere Experiment: Radiation, Aerosol, and Ozone-Deep Convection (STERAO-A) was conducted in northeastern Colorado to study thunderstorm transport and the production of NO_x by lightning. *Dye et al*. [2000] present an overview of the experiment using the 10 July storm as an example. The ONERA VHF lightning mapper was deployed during the experiment to record and characterize the activity of both IC and CG lightning flashes of storms occurring during the experiment [*Defer et al*., 2001]. Reports from the National Lightning Detection Network (NLDN) [*Cummins et al*., 1998] were also used to determine the number, location and currents of CG flashes [*Defer et al*., 2001].

The ONERA system uses interferometry at 114 MHz with a time window of 23 µs [*Laroche et al*., 1994; *Defer et al*., 2001] to determine phase differences between electromagnetic signals radiated from individual components of lightning flashes received at different close antennas. The phase measurements are functions of angular location of the emitting sources. The ONERA lightning mapper uses two independent direction finder (DF) stations, which in STERAO-A were 40 km apart in a north-south configuration (Figure 1). The northern station, ST1, retrieved azimuth, elevation and magnitude of the individual VHF sources while the second station, ST2, gave azimuth and magnitude of the VHF sources. Unfortunately the elevation sensor of ST1 was unable to accurately retrieve sources for elevation angles <8 and >45 degrees, limiting our three-dimensional investigations [*Defer et al*., 2001]. Because the noise level of VHF emission in northeastern Colorado is low, we were able to set the threshold of detection of the system low (-91 dB for ST1 and –95 dB for ST2 for the 10 July storm). Also the 10 July storm was very isolated and was within 20 to 50 km of ST 1 and 40 to 80 km of ST2 (See

Figure 4 in *Defer et al*., 2001). Thus the isolated, relatively close location of the storm and the high sensitivity of the interferometer allow us to detect, locate and study lightning flashes in this storm.

Like other VHF interferometric mapping systems the ONERA system primarily detects VHF radiation from the negative discharge processes, i.e. negative leaders, K changes, dart leaders and recoil streamers. *Shao et al*. [1999], *Shao and Krehbiel* [1996], and also *Thomas et al*. [2001] have shown that although negative leaders and negative fast processes emit significant radiation in the VHF, positive leaders and other positive discharge processes produce little or very weak VHF emission. Obviously, the inability to detect positive portions of lightning discharges leads to underestimates of the total length of discharge channels for individual flashes.

Based on the duration and type of VHF radiation bursts recorded by the ONERA system, one can distinguish between the negative leaders and the fast processes. Negative stepped and dart-stepped leaders emit semi-continuous radiation over longer durations than do fast processes and normally during the first part of a flash. Dart leaders or K change processes produce much shorter bursts of radiation that are intermittent. Both of these kinds of radiation are detected by the ONERA system [*Defer,* 1999; *Defer et al*., 2001]. Because electric field change sensors were not deployed during the STERAO-A project and because of uncertainties in the elevation measurements from the ONERA interferometer, we can not distinguish dart leaders from K change processes based only on the analysis of the VHF signal.

Using the measurements from both DF stations, we isolated the VHF sources for each flash of the 10 July 1996 storm by applying the angular analysis described in detail in *Defer et al*. [2001]. We examined each VHF source to see if it might belong to a given flash by checking if its azimuth as well as its elevation (when reliable) were spatially and temporally close to either the preceding VHF source or those of previous sources already established as part of the flash. If two sources were separated in time by more than 0.5 s, the second source was considered as the beginning of a new flash. (See Section 3 and Figure 2 in *Defer et al*. [2001] for more details). By applying this method, each VHF source was assigned to an individual flash and a list of sources associated with each flash was produced. *Defer et al.* [2001] employed this technique to quantify flash rates and flash characteristics such as flash duration for the entire life of the 10 July 1996 storm. Herein we use the sorted-by-flash data to distinguish different components of a flash and also to estimate the VHF flash length by applying relationships described in the next section.

The analysis described above showed the presence of short duration discharges, i.e. discharges with durations < 1 ms [*Defer et al.* [2001]. Analysis of the locations of the short duration flashes revealed that they occurred in the stronger cells and did not occur in every cell of the storm complex (see Figure 12 in *Defer et al.* [2001]). Also we did not observe any range dependency in the detection of the short duration flashes. Records of many of the short duration discharges showed that the received power was well above the threshold of 91 dB. We are convinced that the short duration discharges are real and not the result of the interferometer missing VHF sources and consequently producing false short duration flashes. Other researchers have also reported short duration discharges, for example *Smith et al.* [1999]. There is discussion in the lightning community as to whether or not they should be called flashes in the traditional sense, but there is little question that they do occur. In our analysis and the discussion below we have considered and counted them as flashes.

3. Methods

Before describing the method we want to give a simplified view of both IC and CG lightning flashes to help the reader better understand our techniques. For more comprehensive descriptions of IC and CG flash phenomena see *Shao et al*. [1995] for CG flashes and *Shao and Krehbiel* [1996] for IC flashes. Using a VHF lightning interferometer combined with slow and fast electric field change measurements *Shao and Krehbiel* [1996] show that IC flashes contain what they term an active and a final phase. The active phase is composed primarily of negative leaders that for a regular IC flash initially move upward from the region of negative charge and then outward into the region of positive charge. During the final phase, fast impulsive K events follow in the same path and direction as some of the previous leaders. Some K events also are detected in the region of negative charge. *Shao and Krehbiel* [1996] explain how these results are consistent with those of previous investigators such as *Ogawa and Brook* [1964], *Proctor*

[1981], and *Krehbiel* [1981] who viewed the K events to be recoil streamers that move back along the path of the leaders. *Shao et al*. [1995] have shown with great detail that negative CG flashes start with negative stepped leaders which originate in the lower part of the negative charge region of the cloud and step towards the ground emitting lots of VHF radiation. Upon approaching the ground a streamer propagates from the ground to initiate the return stroke. Subsequent ground strokes within a flash are usually initiated by dart leaders. Both *Shao and Krehbiel* [1996] and *Shao et al*. [1995] show that the negative leaders of IC flashes are similar to the stepped leaders of CG flashes. Additionally, *Mazur et al*. [1998] have shown that the extensive arms of spider lightning often visible below large decaying storms are negative leaders similar to IC or CG negative leaders and that fast leaders or K changes occur along part of this leader structure. As first pointed out by *Mazur et al*. [1995], but also by *Shao and Krehbiel* [1996] and *Shao et al*. [1995], K events and dart leaders of CG flashes are identical phenomena except that dart leaders come to ground.

3.1. Estimates of flash length from the XY method

One method of estimating flash lengths, called the *XYZ* method by *Laroche et al*. [1999] who introduced this technique, is to determine elementary lengths between two successive VHF sources that have been assigned to a given flash according to temporal and spatial criteria. By summing the distances between the successive sources one can estimate the total flash channel length. If the individual VHF sources could be accurately located and the flash was not too complex (e.g. without K events occurring at the same time as leaders), a good estimate of total channel length might be obtainable. For the ONERA interferometer, as used in STERAO-A, the scatter of locations of individual VHF sources is substantial. This is clearly illustrated in Figure 2. The figure shows the location of VHF sources for a leader and two K events for the flash described in more detail in a following section. This flash was centered at an (X,Y) position of roughly (57,42) which is close to and almost equidistant from both ST1 and ST2. Hence, it is located in a very favorable position for determination of source locations with the interferometer as it was configured for STERAO-A (See Figure 1). Even in this optimum location there is appreciable artificial scatter of the source locations. Part of the reason for this scatter of locations may be because the system does not properly separate the branches occurring within the 23 μs time resolution. The system reconstructs average locations of the VHF sources from the integrated signal over the 23 μs time window and consequently can not resolve the structure of a multi-branched leader. In Figure 2 the global motion of the leader and K events can be followed but the sources tend to be connected across the leader rather than along different branches. Use of this method to estimate cumulative channel lengths clearly leads to overestimates, particularly for the leader, even for this optimally located flash.

Additional artificial spreading of locations of sources occurs when VHF sources are much closer to one-station than the other. The uncertainty in the azimuth determinations of the individual sources from the farthest station causes spreading of the sources along the radial from the closest station. This was true for most of the life of the 10 July 1996 storm. Examples of this dispersion along the radial to the closest station can be seen in Figure 16e in *Defer et al*. [2001] and Plate 1 in *Dye et al*. [2000]. This artificial spread obviously leads to increased estimates of flash length. Another limitation of this method is that the measurements from both stations are needed to determine an XY location. When flashes are much closer to one station than another, the farthest station under-samples the VHF radiation with the lowest VHF magnitude, leading to an under-estimate of flash length.

The 10 July 1996 STERAO-A storm was beyond the range for which the ONERA interferometer has good resolution of the elevation. Thus, we were restricted to doing only an XY analysis and can not distinguish different altitudes of the various sources and components. To clearly indicate that we are using only the XY measurements, in this paper we refer to the XY method rather than the XYZ method. It is hard to know what impact this has on the length estimates.

Because of these issues and the fact that the 10 July 1996 storm was much closer to ST1 than ST2 during much of its lifetime, we feel the *XY* approach substantially overestimates the lightning channel lengths. However, in section 6 we compare estimates from the *XY* approach with the length estimates from the method described below.

3.2. The one-station method

We describe in the present section a method to determine length from the measurements of a single DF station. The technique applies simple relations based on the number of VHF sources and characteristics of the physics of lightning.

3.2.1. Determination of the flash components

In order to differentiate between negative leaders and fast processes and identify individual components within a flash we used the VHF sources sorted-by-flash data described above and the criteria described below. Although there are more recent references describing details of IC and CG flashes, the work of *Kitagawa and Brook* [1960] still provides some of the best information on the statistical difference between IC and CG flashes in terms of time between successive leader pulses (pulse intervals) and durations of leaders. They reported that for leaders of CG flashes the pulse interval indicative of individual steps in the leader had a mean of 80 µs with some up to 250 µs. For leaders of IC flashes they found that pulse intervals extended over a very broad range with a mean of about 650 µs. Ninety percent of the intervals were less than 2 ms but some were up to 10 ms. Thus, with the 23 µs time resolution of the ONERA interferometer we should be able to detect the majority of the steps. In our parameterization two VHF sources are assumed to belong to the same component if the duration between those two sources is less than 2 ms; this is an upper limit that should be valid for both CG and most of the IC leaders.

Kitagawa and Brook [1960] reported that less than 10% of the CG leaders had a duration less than 10 ms while less than 2% of the IC leaders lasted less than 50 ms. *Richard et al*. [1986] reported leader duration for both IC and CG lightning including preliminary breakdown ranging from 10 to a few hundreds of milliseconds. Other detailed analysis of VHF radiation for both IC and CG flashes shows that leader processes including preliminary breakdown can last from a few milliseconds up to 90 ms. [*Rhodes and Krehbiel*, 1989; *Rhodes et al*., 1994; *Shao et al*., 1995; *Mazur et al*., 1995; *Shao and Krehbiel*, 1996]. For fast processes *Proctor* [1981] reported Q noise durations ranging from 10 µs to 2 ms while *Richard et al*. [1986] using 1 µs time resolution reported durations ranging from 10 µs to 1 ms. Based on these results we have considered flash components with durations <2 ms as fast processes, otherwise the component is considered to be a negative stepped leader.

From careful scrutiny of results we noted that sometimes when the initial leader process was intermittent and of short duration (i.e. similar in behavior to fast processes), our criteria identified it as a fast process. This behavior could be the result of weak, undetected radiation by a leader or perhaps from short attempted leaders. Since lightning is initiated by a negative stepped leader process, we treated isolated or short trains of VHF sources recorded before any identified leaders as part of the leader process. An example of this behavior is presented in section 4 during the first 200 ms of the flash.

From these criteria, the VHF sources within a flash are identified as either stepped negative leaders or fast processes. The type of each individual component for both IC and CG flashes is determined according to its duration. Then we estimate the length of the VHF components.

3.2.2 Length parameterization

To derive the length of individual lightning components we use the VHF measurements from one of the DF stations and apply simple relationships deduced from the physics of the lightning flash. Negative leaders are often branched and propagate by steps. The VHF pulses are thought to be associated with the motion of the tip of the discharge [*Proctor*, 1981; *Rhodes et al*., 1994]. Electric field measurements show intervals ranging from 5 to 20 μs during stepped leaders [*Krider and Radda*, 1975; *Krider et al*., 1977]. For a negative CG flash, *Rustan et al*. [1980] noted that the negative downward stepped leader consisted of a succession of 1-μs duration pulses with an interval between pulses varying from 11 μs (at the beginning of the leader) to 1 μs (before the ground connection). *Chen et al*. [1999] reported step intervals of 5-50 μs from optical radiation recorded during a negative downward stepped leader. Thus the literature shows a large range for step intervals. Similarly, a wide range of variation has been reported for the step length. *Uman* [1987] gives step lengths of approximately a few tens of meters. More recently *Chen et al.*, [1999] recorded lengths ranging from 8 to 20 m for downward negative stepped leaders.

Although the 23-μs time window of the interferometer does not allow us to identify different pulses occurring within each time window, we can put lower bounds on the step intervals and step lengths from measured speeds of negative leader propagation. The propagation speed of negative leaders is well documented by *Berger* [1977], *Orville and Idone* [1982], *Proctor* [1981], *Idone* [1992], *Shao et al.* [1995], *Shao and Krehbiel* [1996], *Mazur* [1998] and others to be nominally 10^5 to 10^6 m s^{-1}. The range of speeds from Berger's many photographs of stepped leaders was 1 to 25 x 10^5 m s^{-1}, with an average of 2 x 10^5 m s^{-1}. Similarly many of the investigators listed above most frequently report speeds in the range of 1 to 5 x 10^5 m s^{-1}. Given the 23-μs time window of the ONERA interferometer, if we have one step of 10 m in the 23-μs time window, this corresponds to a speed of 4.3 x 10^5 m s^{-1}. Thus one step of 10 m per time window would be well within the range of observed propagation speeds of negative leaders. But these speeds have been determined by examining the overall distance traversed by the leader process over a known time. Thus it effectively represents the propagation speed of an individual branch of a leader. Because the negative leader structure is branched, more than one branch can be propagating at a given time in the time window of the interferometer.

In our parameterization, we arbitrarily assume that only 1 step occurred during each 23-μs window and we further assume that the step is 20 m long and constant. This takes into account some limited branching and gives an average speed of propagation comparable with those reported above. For more extensive flashes this is a conservative estimate of the degree of branching and hence total leader length.

Knowing the number of time windows in which VHF sources, $N_{sources}$, were recorded during the leader duration, we can estimate the total length of leaders in each flash, $L_{-leader}$, by applying the relation

$$L_{-leader} = l_{step} n_{step} N_{sources} \qquad (1)$$

where l_{step} and n_{step} give respectively the length of a step (20 m) and the number of steps (1) per each 23 μs time window during the negative leader process.

A second radiation regime sensed by the ONERA instrument is associated with the fast processes like K changes or dart leaders [*Defer*, 1999; *Defer et al*., 2001]. The locations of these events show that they occur along part of, or sometimes along all of, the channels previously created by the positive and the negative leaders [*Richard et al*., 1986; *Mazur*, 1989; *Shao and Krehbiel*., 1996; *Defer*, 1999]. *Proctor* [1981] noted that rather than the semi-continuous emission of the stepped leader process, 80% of the fast processes are characterized by a train of pulses occurring over a period ranging from 20 µs to 400 µs. *Shao and Krehbiel* [1996] reported K changes propagating with speeds ranging from 10^6 m s^{-1} to 1-2 x 10^7 m s^{-1} and K bursts up to 5 x 10^7 m s^{-1}. Proctor [1981] reported speeds from 2.5 x 10^6 m s^{-1} to 4.4 x 10^7 m s^{-1} with an average speed of 2.5 x 10^7 m s^{-1}. Dart leader speeds have been measured ranging from 10^6 m s^{-1} to 5 x 10^7 m s^{-1} [*Richard et al*., 1986; *Shao and Krehbiel*, 1996]. While the range of speeds of K changes and dart leaders is large, for our purpose of trying to characterize the length of many flashes over the lifetime of a storm we want to select a speed that might be considered a typical or average speed of fast processes. For 21 dart leaders of natural flashes *Orville and Idone* [1982] found an average speed of 1.1 x 10^7 m s^{-1} and *Jordan et al.* [1992] reported an average speed of 1.5 x 10^7 m s^{-1} for 9 dart leaders. Unfortunately, there are relatively few studies showing average speeds of a large number of fast events. A speed of 10^7 m s^{-1} is in the mid range of the speeds given in many of the references. Thus we assume that the fast processes propagate at the constant speed of 10^7 m s^{-1} from their beginning to their end. We believe this is likely to be representative of the majority of fast processes occurring in thunderstorms.

We deduce the length of a fast process component by applying the relation,

$$L_{Fast} = l_{Fast} n_{Fast} \qquad (2)$$

where n_{Fast} is the number of VHF sources associated with a given fast process, and l_{Fast} is the elementary distance deduced from the product of the fast process speed and the time window of the lightning mapper (10^7 m s^{-1} x 23 x 10^{-6} s = 230 m).

When flashes are close to ST1, the elevation measurements from the ONERA instrument seem reliable. For these close flashes we can distinguish dart leaders from K events and observe that the radiation from dart leaders is similar to radiation from K events as previously reported by *Rhodes et al.* [1994] and *Shao et al.* [1995]. But without good elevation measurements we can not distinguish between dart leaders and K events from the VHF emission. We also investigated using stroke reports from the NLDN, but *Defer et al.* [2001] compared NLDN reports to VHF radiation signatures of CG strokes for the July 10 storm and estimated that the NLDN stroke detection efficiency ranged from 50% to 80% based on the VHF signature of the downward negative stepped leader-return stroke process. Because of its low detection efficiency for strokes we did not use the NLDN stroke reports to identify dart leaders. Thus in this study dart leaders are treated the same as K changes. Because dart leaders and K changes have similar speeds of propagation [*Shao et al.*, 1995], this assumption should not impact our length estimates.

The return stroke process is known to be fast and energetic. During negative CG flashes VHF radiation is recorded mostly as a consequence of the upward propagation of the return stroke along the intra-cloud part of the flash. Our representation does not specifically take into account the length of return strokes, which are known to follow upward back along the path of downward moving negative stepped leaders or dart leaders. VHF sources recorded during return stroke process are considered as part of the stepped or dart leaders. Because there were relatively few CG flashes for the 10 July storm this is not a large source of error. Finally, the positive leaders and positive strokes are not considered in the present parameterization because the interferometer does not detect them.

4. Examples of flashes

In this section, we illustrate the technique described in section 3 for an IC and a CG flash recorded during the 10 July 1996 STERAO-A storm.

4.1. An IC flash

Figure 3 shows the time evolution of the azimuth and magnitude of the VHF sources recorded by the two DF stations for an IC flash. The lightning flash lasted for about 490 ms and was composed of successive components radiating in the VHF domain. ST1 recorded 1182 VHF sources while only 653 VHF sources were recorded at ST2, probably because the flash was further from ST2.

The VHF radiation of this IC flash had two regimes. The first regime (until time 300 ms) consisted primarily of four relatively continuous events of radiation with relatively long periods (labeled e2 to e5 in Figure 3b). Event e1, which occurred earlier, contained very few VHF sources. The second regime (after time 300 ms) was composed of short-duration components. By analyzing the VHF magnitude and the azimuth of the VHF sources, we noted that the development of this flash is similar to the IC flash described in *Shao and Krehbiel* [1996]. The first regime is associated with the development of the negative leaders, while the second regime is the junction phase of the flash and the motion of K change processes. Unfortunately the flash was too far from ST1 for reliable elevation measurements so we can not tell if the negative leaders were propagating upward, which is the typical motion of a normal IC flash as detailed in *Shao and Krehbiel*. [1996], or downward, as observed by *Krehbiel* [2001] for an "inverted" IC flash.

The slow motion of the five first events of the flash and the semi-continuous emission tell us these are negative stepped leaders. Event e1 was composed of only a few VHF sources, while event e2 starting at the same location as e1 contained more sources. Event e3 was only partially recorded by ST2 (Figure 3d) probably due to a weak VHF signal that was lower than the applied threshold. For event e4 very few sources were recorded and only at ST1. Finally event e5 propagated at different azimuths than e1-4 (Figure 3b) suggesting the development of a new main negative branch.

Most of the VHF sources of the second regime after 300 ms were located in the same angular sector as the one used by e5 (Figures 3b and c). Because of the short duration and rapid motion we identify these events (e.g. LK-1, LK-2) as K changes. They propagated mainly in the area where negative leaders had propagated earlier but perhaps also in regions of positive leaders not seen by the interferometer, as suggested by *Mazur* [1989].

Using the techniques described in section 3 we have estimated the lengths for the three components of the flash labeled in Figure 3 as e5, LK-1 and LK-2. Event e5 had a length of 9.5 km from ST1, 8.3 from ST2, and 184 km from the *XY* method The lengths for leader e5 are a factor of almost twenty larger for the *XY* method than the one-station method, primarily due to the scatter of locations of the many VHF sources within the leader as seen in Figure 2. LK-1 and LK-2 had lengths of 19 km and 12 km from ST1, 15 and 11 km from ST2, and 33 and 19 km for the *XY* method, respectively. The difference in lengths between ST1 and ST2 measurements is due to the difference in the number of

VHF sources recorded by each station. Fast processes LK-1 and LK-2 correspond to long K change processes which propagated successively along not only the negative leader channels (e.g. e5) but probably also along ionized paths created by undetected positive leaders, thus LK-1 and LK-2 lengths from the one-station method are longer than the negative leader e5. Additionally, the assumptions made for leaders in the one-station method may be underestimating lengths for multi-branched leaders such as this one. The total component channel length of this entire IC flash was 68 km (45 km) from the measurements of ST1 (ST2) and 288 km for the *XY* method. The percentage of the total length due to leader processes was 28% from ST1, 22% from ST2 and 64% from the XY method.

4.2. CG flashes

Defer et al. [2001] identified concurrent NLDN and ONERA measurements of CG flashes recorded during the 10 July 1996 STERAO-A storm. Figure 4 shows the VHF radiation recorded by ST1 and ST2 for one of these negative CG flashes (0010:30 UT). The NLDN recorded two strokes for this flash. This flash is also described by *Defer et al*. [2001], see Figure 16. Applying the one-station method to the VHF radiation recorded by ST1 we calculated a total length of about 9 km for the downward negative stepped leader of the first connection to the ground. The length of the dart leader of the second stroke to ground was estimated at 5.5 km. A total length of 35 km was computed for all components of the CG flash with the length of the preliminary breakdown plus the downward negative stepped leader representing 32% of the total VHF length. Using the *XY* method, we obtained lengths of 172 km, 18 km and 282 km, respectively, for the first downward negative stepped leader, for the second connection to the ground and for the entire flash.

For another negative CG flash (0014:20 UT), the first negative downward stepped leader (stroke #0 in Figure 18 of *Defer et al*.) was 8.5 km long from ST1 measurements, while a length of 2.6 km was computed for the second downward stepped leader (stroke #1 in *Defer et al.*). The total length of this flash was estimated to be 61 km. The leader processes all occurred during the first 150 milliseconds of the flash and contributed 49% of the length. For comparison, a positive CG flash that occurred at 0000:05 UT

(Figure 17 in *Defer et al*. [2001]), gave a total VHF length of about 32 km based on ST1 measurements.

5. Uncertainties and Sensitivity of Assumptions

Some of the uncertainties associated with our estimates of lightning channel lengths is due to the limitations of the interferometer. Others are introduced in the one-station method by the assumptions we have made on step lengths, intervals between steps and speeds of propagation of fast processes. If we were trying to estimate lengths for only a few flashes a more comprehensive approach might be taken. But this seemed infeasible for studying flashes over the lifetime of a storm that lasted 4 1/2 hours and produced over 5000 lightning flashes.

A major uncertainty obviously comes from the parameters and relationships assumed in the one-station method. In order to examine how much the assumptions impact our estimates we have investigated the sensitivity of these assumptions for the IC flash presented in section 4.1. Figure 5a shows the variation in estimated length for the one-station method as the number of steps occurring during the 23 μs time window is increased from 1 to 20 steps, while the other parameters are held constant. As expected from relation (1) leader length is a linear function of the number of steps and the estimated length increases from 68 km to 438 km, about 6.5 times greater. This same plot can be used to study the sensitivity of the step length. If the step length increases from 0.02 to 0.4 km (20 to 400 m) the total VHF length increases from 68 to 438 km (with the number of steps constant at 1 step per time window). However, the step length and the number of steps per time window are not totally independent. The total distance propagated per time window should not exceed known stepped leader velocities of 10^5 to 10^6 m s^{-1}. This places some limitations on the combination of step length and number of steps per time window. As discussed earlier, one step of 10 m length per 23 μs time window would give a propagation speed of 4.3 x 10^5 m s^{-1} which is within the range of known propagation speeds of negative leaders. This one step, however would be for only one branch of a branched leader. Other branches could be occurring at the same time within the 23 μs window. We used 20 m per time window to partially account for branching, but for many flashes, especially later in the life of the storm, the branching is more extensive. In these cases our assumptions probably underestimate leader lengths. On the other hand, the duration of a leader is a partial measure of the degree of branching. Short leaders have shorter durations. If locations of the individual VHF sources could be accurately determined, the *XY* approach could more naturally give an estimate for branching. But as we saw from Sections 3.1 and Figure 2 the present system does not have sufficient accuracy.

We also investigated the total VHF length as a function of the speedy that we assumed for the fast processes. Figure 5b shows that when the constant speed assumed for a fast process is increased from 10^6 m s^{-1} to 5 x 10^7 m s^{-1} the length increases from 24 to 261 km, a ten-fold increase. Although speeds of individual K changes and dart leaders have been observed to vary over this wide range, the average speed for most fast processes is likely to be in the middle of this range. The more commonly referenced values in the literature are between 5 x 10^6 to 2 x 10^7 m s^{-1}. This suggests that by assuming a propagation speed of 10^7 m s^{-1} the uncertainty in our length estimates for fast processes would be roughly a factor of 2.

As we stated in Section 2 another source of error is that the interferometer poorly detects positive discharge processes. As a consequence we underestimate the lengths of both leaders and fast processes. There currently is much debate in the lightning community over whether leader propagation is a bi-directional leader process. Even if the leader process is bi-directional, our leader estimates are at the most off by a factor of two and most likely less as a result of undetected positive leaders. As reported by *Mazur* [1989] some K change processes propagate in positive leader channels. However, the ONERA system was unable to accurately retrieve the altitude of the VHF sources limiting our investigation of the channel extension of the positive leaders that could be inferred from the locations of the K change processes. For future studies a combination of time of arrival VHF mapping systems such as that of *Krehbiel* [2001] in conjunction with high time resolution interferometers could provide better estimates of channel length. The time-of-arrival instrument can give an image of the skeleton of the flash (positive and negative branches), while the interferometer could give the development of the negative processes and fast processes as described by *Defer et al*. [2000].

An additional source of error, as pointed out by *Mazur et al.* [1998], is that with the 23 μs time window of the interferometer measurements we are not able to fully isolate VHF radiation from K events that might be happening within an extensive leader structure such as occurs in spider lightning. Further investigations with high time resolution instruments would help us to quantify how often such events occur.

Other possible sources of error are flash, component and VHF source detection efficiencies. Because of the attenuation of the VHF signal between the source location and the interferometer and because of characteristics of VHF radiation (amplitude, pulse rate within the time window, and pulse width), the level of the integrated signal can be below the acquisition threshold for a DF station. For the present study, we believe that the flash detection efficiency is very close to 100%. For the component detection efficiency, we believe that most of the components with strong VHF radiation were recorded by the two interferometers. For the CG flash population, all events reported by the NLDN as ground strokes were also sensed by the interferometers [*Defer et al*., 2001] suggesting that here again the highly radiative, pre-stroke phenomena within a flash were recorded. We believe that only a few of the IC negative leaders might not have been detected due to an integrated signal below the acquisition threshold. An example of this is event e3 in Figure 3 for the IC flash described above. ST1 recorded radiation while ST2 did not. It is difficult to quantify the uncertainty in our length estimates. Based on the discussion above our best estimate of the uncertainty from the one-station method is a factor of 2 to 3. Because our assumptions were deliberately conservative and because most of the sources of error would lead to underestimates, the lengths determined using the one-station method are likely to be underestimates rather than overestimates, particularly for leaders. The difference in length estimates from ST1 and ST2 using the one-station method give an idea of the underestimate in length resulting from the under-detection of VHF sources by ST2 compared to ST1. This difference varies a little with time but generally is about a factor of two. As discussed in section 3.1 and 4.1 and shown dramatically in Figure 2, we believe the lengths determined by the XY method are greatly overestimated, particularly for leader processes. The length of leader e5 in Figure 2 was about 20 times larger than the lengths determined from either ST1 or ST2 from the one-station method. In spite of this uncertainty the analysis does reveal interesting variations in channel lengths produced per unit time period as the storm evolves. While there may be uncertainty in the absolute lengths we have determined, the evolving character of the storm that the measurements show are likely to be real variations occurring within the storm during its 4 1/2 hour lifetime.

6. Analysis of the 10th July 1996 storm

The time evolution of the lightning activity in the 10 July 1996 STERAO-A storm is summarized in Figure 6 based on the one-station method. A more detailed description of lightning in this storm is given in *Defer et al*. [2001] who showed that the activity was predominately IC with less than 2% of the total flashes (83 CG flashes out of 5428 total) connecting to the ground. Figure 6a shows that the first major peak of the lightning activity occurred at 2320 UT with 189 flashes per 5-min period. The largest peak was recorded at 0120 UT with 248 flashes per 5-min period with a secondary peak 45 min later (195 flashes per 5-min period). Figure 6b shows that from 2200 to 2230 UT 15 to 20 % of the flashes were CG flashes. From 2240 to 2350 there were only a few CG flashes. More CG flashes occurred again from 2350 to 0030 UT when new small cells were developing in the storm complex. The percentage of short duration flashes (Figure 6c) also varied during the life of the storm. From 2340 to 2330 UT, 20 to 30 percent of the flashes were of short duration (Figure 6c). Analysis of the locations of the short duration flashes revealed that they did not occur in every cell of the storm complex (see Figure 12 in *Defer et al.* [2001]), but were associated with the stronger cells of the storm.

6.1. Length of individual flashes

The lengths of all individual flashes derived from ST1 measurements using the one-station method are shown in Figure 7 for the 4 1/2 hour life of the storm. Each *plus* represents the length of one flash. The variations in flash length show a correspondence with changes in the storm behavior and the type of lightning. See *Dye et al*. [2000] for a description of the overall storm behavior. At the beginning of the storm when there were a couple of moderate intensity cells and a high percentage of CG flashes, the lengths are on average longer than after 2240 UT. From 2240 to roughly 2400 UT, when the storm was intensifying in the multi-cellular stage and the flashes were largely IC (Figure 6b), there is a high percentage of flashes shorter than a few kilometers. From then until near the end of the storm the flash lengths extended over a broad range from <1 km to >100 km. As the storm became supercellular from ~0030 UT to the end of the storm, the percentage of flashes longer than 10 km gradually increases.

The derived total channel lengths of the individual flashes in the storm ranged from 0.02 km to 474 km, with an average value of about 19 km (34 km if we exclude all derived lengths less than 1 km). The smallest VHF flash lengths correspond to single source flashes and are categorized as leaders according to the algorithms discussed in section 3. The largest length was recorded at 0222:58 UT for an IC flash that occurred very near the end of the storm. The long flashes are complex flashes characterized by multi-branched leaders, intense radiation in the VHF domain, and a large number of components.

Figure 8 gives the total VHF length of individual flashes as a function of the flash duration measured at ST1. The duration is determined from the maximum time separation between the first and last VHF source for that flash recorded at ST1. The flash duration ranged from 23 μs to 1.8 s [*Defer et al.*, 2001]. For short duration flashes, i.e., those <1 ms, the length does not exceed 1 km. With the one-station method this category of flashes are considered as leader events. For flashes with durations >1 ms, the length estimates separate into two populations of flashes. The first population, with lengths mostly <3 km, is associated with flashes characterized by very little radiation. For these flashes, the ONERA system detected very few VHF sources even though the duration for some flashes extended up to almost half a second and the magnitudes of the detected radiation was strong. In the second population, the flashes are longer, exhibit more branching, contain many leaders and fast processes, and have many more VHF sources that are radiatively intense. Examples of these complex flashes are shown in *Defer et al.* [2001], Figure 2, which presents a 1.4 s time series of angular locations of VHF sources. Flashes 1, 3, 4 and 5 in that figure as well as the IC and CG flashes shown in Section 4 of this paper belong to this more complex flash category. For this population of flashes, the total VHF length increases when the duration increases. However, for a given duration the total VHF length varies over one order of magnitude, while for a given length, the flash duration varies over less than one order of magnitude. This suggests that different lightning flashes of similar duration do not exhibit either the same number of components, the same component duration or the same component extensions.

Figure 9 shows the percentage of flashes for the entire storm as a function of uniform logarithmic length intervals for independent measurements from ST1 and ST2. As expected, the lengths from ST2 are shorter, because ST2 was farther from the storm. Based on ST1 measurements 47%, 18% and 33% of the flashes in this storm had a total VHF length between the respective intervals [0.02 km to 1 km], [1 km to 10 km] and [10 km to 100 km]. Most of the flashes from both ST1 and ST2 had total lengths less than 100 km.

Figure 10 shows the lengths from ST1 for flashes identified as negative or positive CG flashes by the NLDN. For the 70 negative CG flashes, the mean VHF flash length was 61 km. For the 13 positive CG flashes the mean was about 43 km. Based on ST1 measurements 85% (77%) of the negative (positive) CG flashes had a VHF length between 10 and 100 km. Negative CG flashes with estimated lengths below 10 km did not contain downward stepped leaders. The received signal strength was probably below the acquisition threshold. Alternatively, they could also have been misidentified by the NLDN.

6.2 Total and average lengths of flashes per 5-min period

The time evolution of the sum of the individual flash lengths occurring during each 5-min period of the storm’s lifetime derived from the one-station method for both ST1 and ST2 measurements is shown in Figure 11. During the period after 0100 UT, when the storm was in its supercell stage, the maximum sum of total length per 5-min period was about 5400 km from ST1 and 2200 km from ST2. The total VHF length estimated from ST1 for all lightning flashes for the entire life of the storm is about 102,000 km. The estimates of total length per 5-min period for ST2 are lower than ST1 by a factor of two over most of the storm history except during the first hour. During this period they were comparable. A high percentage of CG flashes were occurring during this period and apparently the VHF radiation from them was sufficiently strong to be detected by both stations. The difference between the two stations after 2330 UT shows the importance of detecting as many VHF sources as possible. For comparison Figure 11 also plots the total VHF length per 5-min period based on the *XY* method. It reached a maximum value of 50,000 km per 5 min period, a factor of almost 10 greater than the one-station method using ST1. The total lightning channel length for the entire storm from the XY method exceeded 677,000 km.

Figure 12 reports the time evolution of the average length per flash per 5-min period, which we obtained by dividing the total VHF length per period by the number of flashes recorded during that period. From ST1 measurements, the average length per flash ranged from 2 to 143 km while ST2 measurements ranged from 1 to 112 km. The pattern of average length per flash follows the lightning characteristics of the storm. When negative CG flashes were occurring between 2150 and 2245 UT (See Figure 6b) the average length per flash from ST1 shows a peak with a maximum of almost 35 km. Between 2230 and 2340 UT the flashes were primarily IC and the average flash length is relatively low (2-15 km). After 2350 UT until 0200, the average length per flash gradually increases as the storm evolves into the supercell stage. During the decay phase of the storm after 0215, the average length per flash increases sharply to just over 100 km. Note that the difference in average flash lengths between ST1 and ST2 from 2330 to 0215 UT is approximately a factor of two.

We have also plotted the average length per flash per 5 min period from the *XY* method in Figure 12. Note that these estimates are a factor of 5 to 10 greater than the estimates from ST1 using the one-station method and that this ratio remains roughly the same throughout the 4 ½ hours of the storm life. Interestingly, variations are very similar for the three traces but the magnitude differs.

The time evolution of the percentage of total flash length that is due to leaders is reported in Figure 13. This percentage shows a lot of variability throughout the storm especially between 2200 and 2330 UT but with lots of variation.. After 2330 until 0145 the percentage of leader lengths gradually increases from ~15 to ~25%. During the intense multi-cellular stage from 2315 to 2345 (See *Dye et al.* [2000]), the percentage of leaders is less than at other times. There is not an obvious association with the occurrence of CG flashes at the beginning of the storm or again near 2345 to 0030 UT.

7. Summary and Discussion

We have described two techniques, the *XY* method and the one-station method, which we have used to estimate the length of individual lightning flashes utilizing the VHF radiation from lightning detected by the ONERA lightning interferometer. We have shown that the XY locations of VHF sources derived from the interferometer measurements from STERAO-A are not sufficiently accurate by themselves to be able to describe precisely the path that different components of a flash traverse. There is a lot of scatter in the locations determined for the recorded VHF sources. Hence, we can not directly determine the lengths of flashes nor lengths of the different components of a flash using the *XY* method. Our results suggest that total lightning lengths derived from this method may be overestimated by as much as a factor of 5 to 10. They could be considered as upper bounds for total flash length.

Because results from the XY method seemed unreasonable, we developed the one-station method to estimate lengths of negative leaders and of negative fast processes. It is based on the reports in the literature of the step lengths, step intervals and speeds of propagation of negative leaders and speeds of propagation of K events and dart leaders reported by other investigators. We can distinguish between negative leaders and K events or dart leaders because of the differing physical nature of propagation of the negative leaders and fast processes and the consequent difference in VHF emissions. These differences have been discussed by many previous investigators and we have also seen them with the ONERA interferometer measurements. In section 5 we discussed the uncertainty and possible sources of error that the estimates from this method might have. We believe that our estimates of length from the one-station method may be in error by a factor of 2 to 3, but these estimates are more likely to be underestimates than overestimates, particularly for leaders, for several reasons: *i*) Our assumptions were deliberately conservative. *ii*) The interferometer (like other VHF techniques) detects primarily negative discharge processes not positive leaders and streamers. *iii*) Multiple branches of complex leaders may be under represented. And, *iv*) Some fast processes may be obscured by simultaneously occurring extensive leaders.

Although there may be uncertainty in the absolute lengths determined using the one-station method, the results presented in Section 6 show temporal similarity between the *XY* and the one-station methods. Additionally, the variations in average flash lengths and total flash length per 5 min period closely follow the pattern of CG and IC flashes observed in the storm. This similarity between the two totally independent techniques plus the correspondence with different types of lightning gives support to the notion that the variations in total lightning channel lengths observed during the lifetime of the 10 July 1996 storm are real.

As far as we know, there have been no attempts to investigate the evolution of the length of flashes over the lifetime of a storm or the total channel length of flashes including both leaders and fast processes. Much of the previous literature has dealt with the length of the return strokes of CG flashes or the total extension, i.e. the maximum distance traversed by a flash. For example, *Krehbiel* [1986] reported the length of a CG flash to be 5 to 7 km. *Ogawa and Brook* [1964] estimated the length of an IC flash to be 1 to 6 km. *MacGorman* [1978], reported flashes extending over 10-20 km on the basis of acoustical measurements. *Rison et al.* [1999] presented time-of-arrival VHF observations in central New Mexico storms for IC and CG flashes with extensions greater than 15 km. *Krehbiel et al.* [1998] reported a 75 km extensive IC and CG flash recorded in central Oklahoma. *Ligda* [1956] showed a discharge over 150 km in length. *Defer et al*. [2000] reported K change events longer than 20 km from a combined analysis of interferometer and time-of-arrival measurements of an IC flash in Florida. Recent observations of lightning flashes from the New Mexico Tech lightning mapping system show very extensive branching and flashes extending over a very large area [*Thomas et al*., 2000, *Krehbiel*, 2001]. The sum of channels in branched negative leaders, the ensuing K events, and possible undetected positive leaders and streamers clearly can lead to large total channel lengths. Our results on total channel lengths from the one-station method are consistent with lengths of different flash components reported in the literature.

In addition to examining flash length characteristics over the lifetime of this storm, another goal of this study has been to try to provide another approach to examining the production of NO_x by lightning. Previous studies have examined lightning production of NO_x based on the number of flashes occurring globally or in a storm. But measurements clearly show that flash type, duration, current and energy vary widely from storm to storm and within a storm. For example, for the 10 July 1996 storm we show that flash rates vary over 2 orders of magnitude and flash durations vary over almost five orders of magnitude. We also show that for a given flash duration, the total length could range over one order of magnitude, suggesting that the number of flash components and/or the length of components have large variations per flash. NO_x production per flash must have a similarly large variation without even considering the different NO_x production rates for different flash components. Even if we were able to quantify total lightning flash rate globally, regionally, or within a storm, substantial uncertainty in NO_x produced per flash or per storm would remain.

Additional complexity is introduced because lightning detection systems differ in terms of the type of lightning detected and the detection efficiency. Our measurements are from a sensitive lightning interferometer with time resolution of 23 μs that detects both IC as well as CG flashes. These can not be compared to the NLDN that detects only CG flashes or satellite sensors, such as NASA's Optical Transient Detector or Lightning Imaging Sensor, which use 2 ms time resolution [*Christian et al.*, 1996] but probably detects IC flashes more efficiently than CG flashes [*Thomas et al.*, 2000]. Consequently NO_x production based on the currently observed number of flashes has a lot of uncertainty.

Knowledge of the length of discharge channels within storms, within flashes or within given time periods provides an alternate approach for examining NO_x production by lightning, especially in conjunction with accompanying in-situ chemical measurements. For this reason we investigated the length of lightning channels in the 10 July 1996 storm. There is also considerable uncertainty in the length approach. As discussed in Section 5 we suggest that there is roughly a factor of 2 to 3 uncertainty in determination of total lightning lengths using the one-station method from the ONERA interferometer measurements made during STERAO-A. The technology of this instrument is now more than a decade old. If the newly developed time of arrival systems, such as that of *Krehbiel* [2001], were combined with a high time resolution interferometer system, more reliable estimates of total lightning lengths are possible.

Another major uncertainty in using lightning lengths to investigate lightning produced NO_x is that there is likely to be considerable variation in NO_x production per unit length for different lightning components. The two orders of magnitude variations of

NO_x per meter observed in plumes of different flashes by *Stith et al.* [1999] and *Huntrieser et al.* [*in press*] strongly suggest this.

The results from this study have been used in a companion paper by *Skamarock et al*. [2002] to examine NO_x production per unit channel length for the 10 July 1996 storm. That paper uses the results of a cloud simulation [*Skamarock et al*., 2000] to estimate the transport of NO_x into the anvil from lower levels and uses in situ measurements of NO_x [*Dye et al*., 2000] to determine the flux of NO_x into the anvil. The estimates of flash length reported in the present article are then combined with the flux of lightning produced NO_x in the anvil to determine NO_x produced per unit lightning channel length, produced per flash, and estimates of the total NO_x potentially produced by the 10 July 1996 storm.

Skamarock et al. conclude that, even with the use of lightning lengths, large uncertainty remains in our knowledge of the global contribution of lightning to the production of NO_x. Perhaps by the use of improved lightning mapping techniques in conjunction with geo-synchronous satellites, additional field studies with in situ chemical measurements in thunderstorms in other parts of the world (particularly the tropics), and laboratory investigations of NO_x production by different lightning components we can eventually reduce the uncertainty in estimates of the global production of NO_x by lightning.

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FIGURE CAPTIONS

Figure 1. Map of the STERAO-A experimental area showing the location of the CSU-CHILL radar (range rings every 30 km) and the two remote stations, ST1 and ST2, of the ONERA lightning interferometer system. Azimuth directions of 0º, +45º and +90º relative to ST1 and ST2 are shown. White zones define the area where XY locations can be determined for VHF sources.

Figure 2. XY locations projected to the ground of the VHF sources recorded during a) the leader process e5 in Figure 3 and b) and c) two K events, LK-1 and LK-2 of Figure 3. Two successive sources are joined when there was < 200 μs between them. The arrows indicate global motion of the discharges.

Figure 3. VHF measurements recorded during an intra-cloud flash that occurred at 0200:26 UT in the 10 July 1996 storm. Panels (a) and (b) report the time evolution of the magnitude of the received VHF signal and the retrieved azimuth from ST1. Panels (c) and (d) show the time evolution of the retrieved azimuth and the magnitude of the received VHF signal from ST2.

Figure 4. VHF measurements recorded during a cloud-to-ground flash that occurred at, 0010:30 UT in the 10 July 1996 storm. Panels (a) and (b) report the time evolution of the magnitude of the received VHF signal and the retrieved azimuth from ST1. Panels (c) and (d) show the time evolution of the retrieved azimuth and the magnitude of the received VHF signal from ST2. Triangles on the absicca indicate times of ground connections as reported by the NLDN.

Figure 5. Sensitivity of the length parameterization applied to ST1 measurements for the IC flash described in Section 4.1. Variation of total length, leader length and K change length as a function of (a) the number of steps and (b) different fast process speeds, with the other parameters held constant.

Figure 6. (a) Time evolution of the total flash rate, (b) CG/(IC+CG) ratio, and (c) the ratio of short-duration to total flashes.

Figure 7. VHF flash lengths retrieved from ST1 measurements plotted on a logarithmic scale for the entire life of the storm. Each plus represents an individual flash.

Figure 8. Total VHF flash length (on a logarithmic scale) as a function of the flash duration (on a logarithm scale) based on ST1 measurements.

Figure 9. The distribution of flash lengths from ST1 and ST2 measurements indicated by the solid and dashed lines, respectively. The abscissa is plotted on a logarithmic scale.

Figure 10. The distribution of lengths for CG flashes from ST1 measurements. The abscissa is plotted on a logarithmic scale.

Figure 11. Total VHF flash length per 5-min period for the entire life of the storm using the one-station method with measurements from ST1 (solid, bold line) and ST2 (dotted line) and also using the XY method (thin, solid line with diamonds).

Figure 12. Average VHF flash length per 5-min period during the entire life of the storm using the one-station method with measurements from ST1 (solid, bold line) and ST2 (dotted line) and also using the XY method (thin, solid line with diamonds).

Figure 13. Percentage of the length due to leader processes based on ST1 measurements plotted for the entire life of the storm.

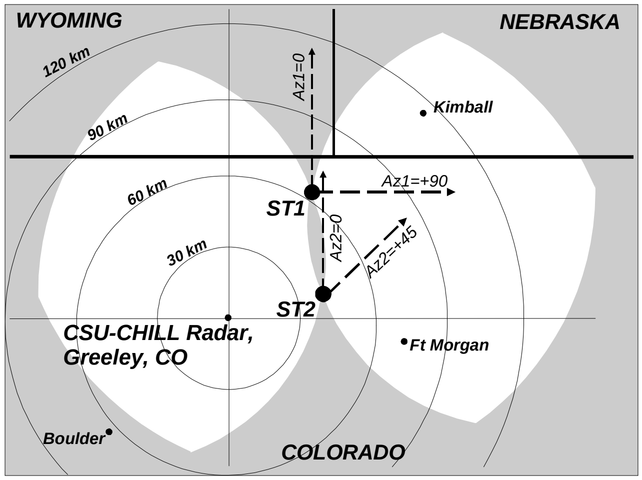

WYOMING
NEBRASKA
120 km
90 km
60 km
30 km
Az1=0
Kimball
Az1=+90
ST1
Az2=0
Az2=+45
ST2
CSU-CHILL Radar,
Greeley, CO
Ft Morgan
Boulder
COLORADO

Figure 1

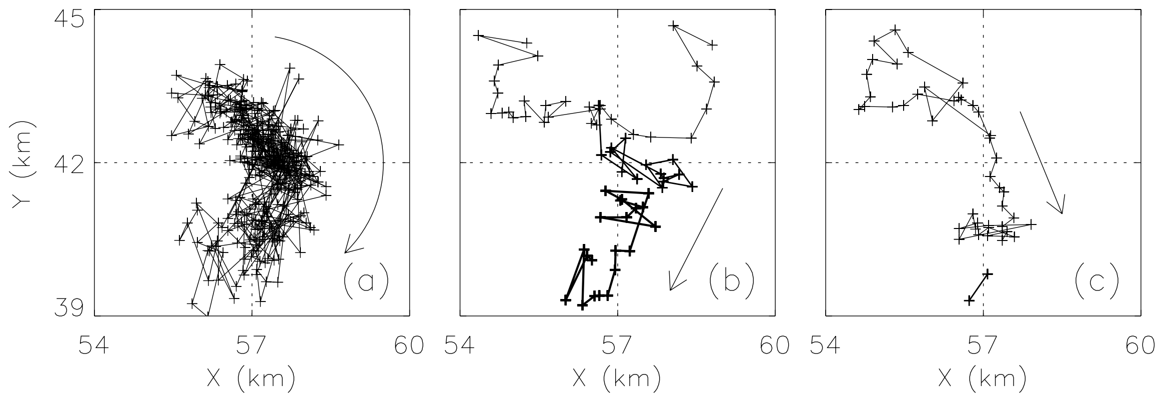


Figure 2

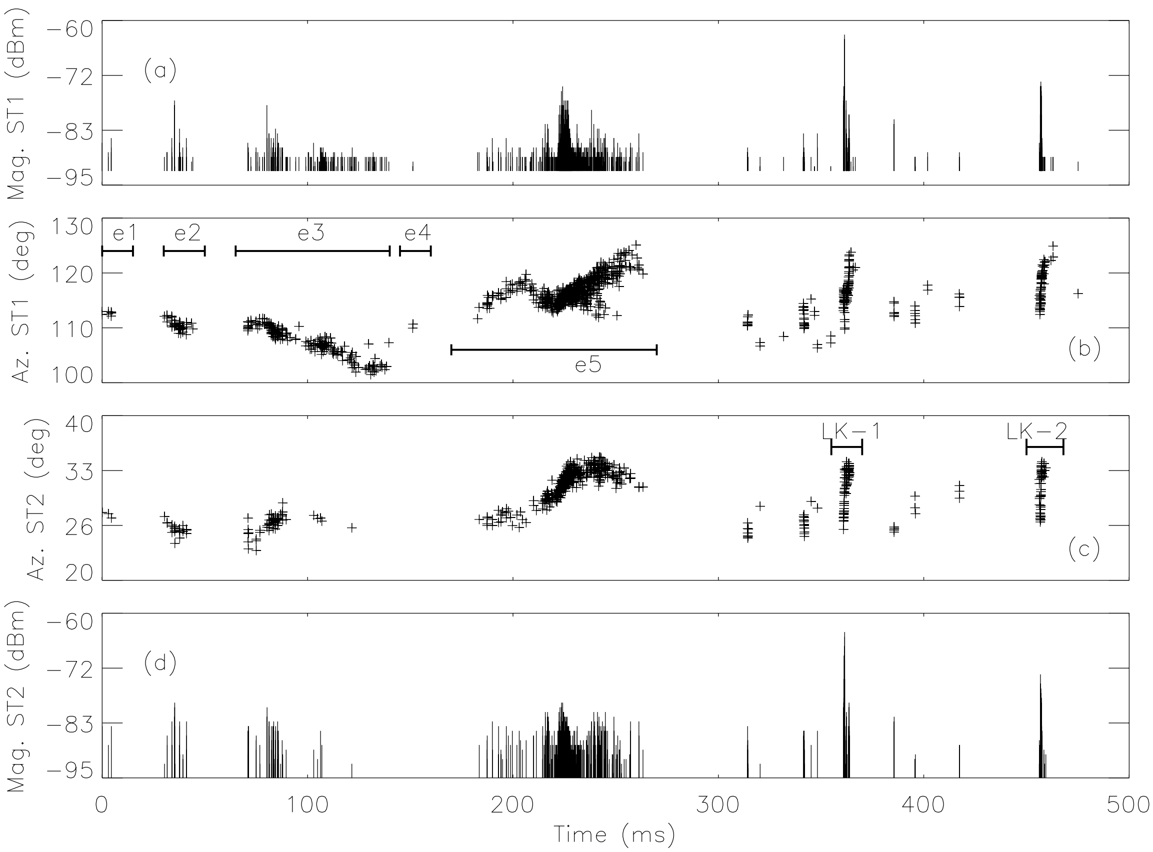
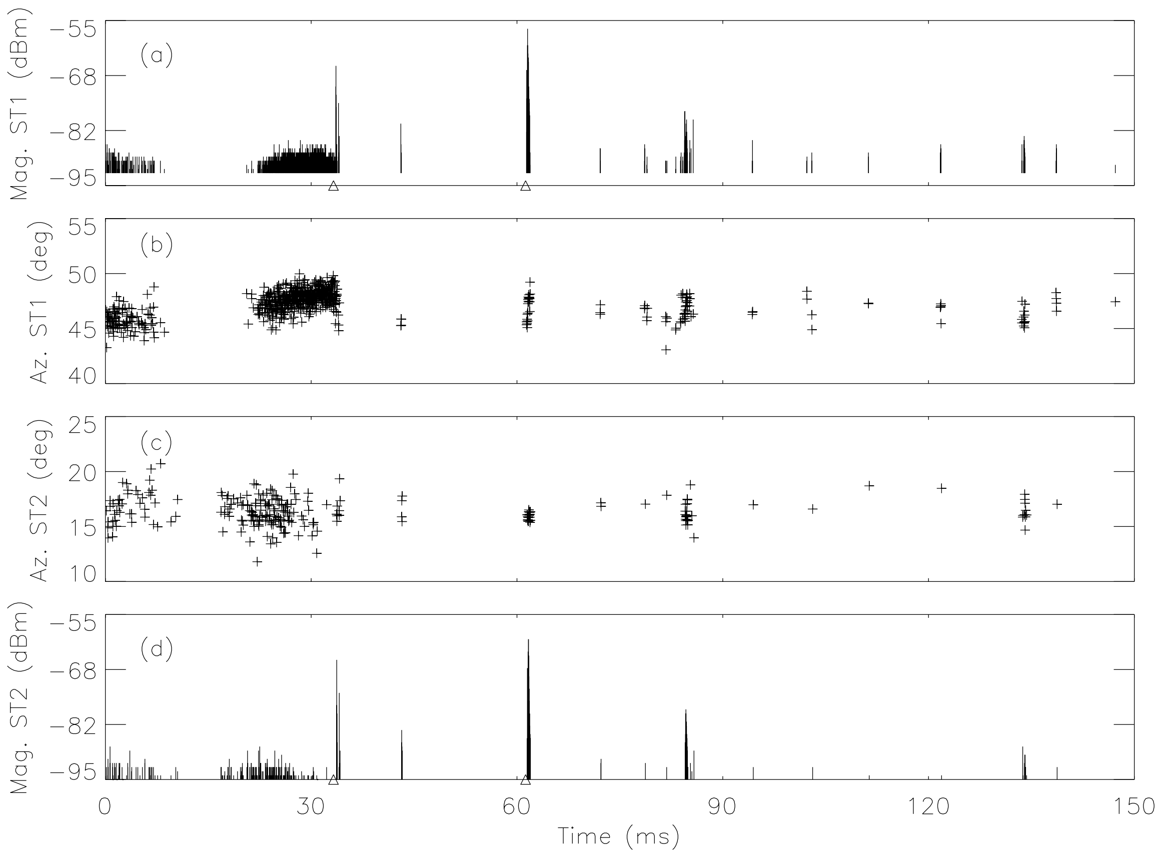

Mag. ST1 (dBm)
-60
-72
-83
-95
(a)
Az. ST1 (deg)
130
120
110
100
e1
e2
e3
e4
e5
(b)
Az. ST2 (deg)
40
33
26
20
LK-1
LK-2
(c)
Mag. ST2 (dBm)
-60
-72
-83
-95
(d)
0
100
200
300
400
500
Time (ms)

Figure 3



Mag. ST1 (dBm)
-55
-68
-82
-95
(a)
Az. ST1 (deg)
55
50
45
40
(b)
Az. ST2 (deg)
25
20
15
10
(c)
Mag. ST2 (dBm)
-55
-68
-82
-95
(d)
0
30
60
90
120
150
Time (ms)

Figure 4

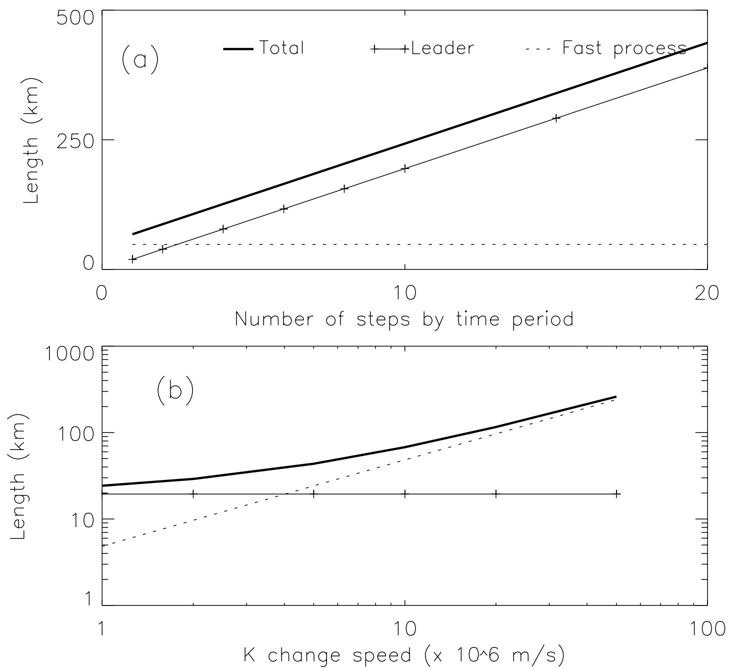

(a)
Total
Leader
Fast process
Length (km)
500
250
0
0
10
20
Number of steps by time period
(b)
Length (km)
1000
100
10
1
1
10
100
K change speed (x 10^6 m/s)

Figure 5

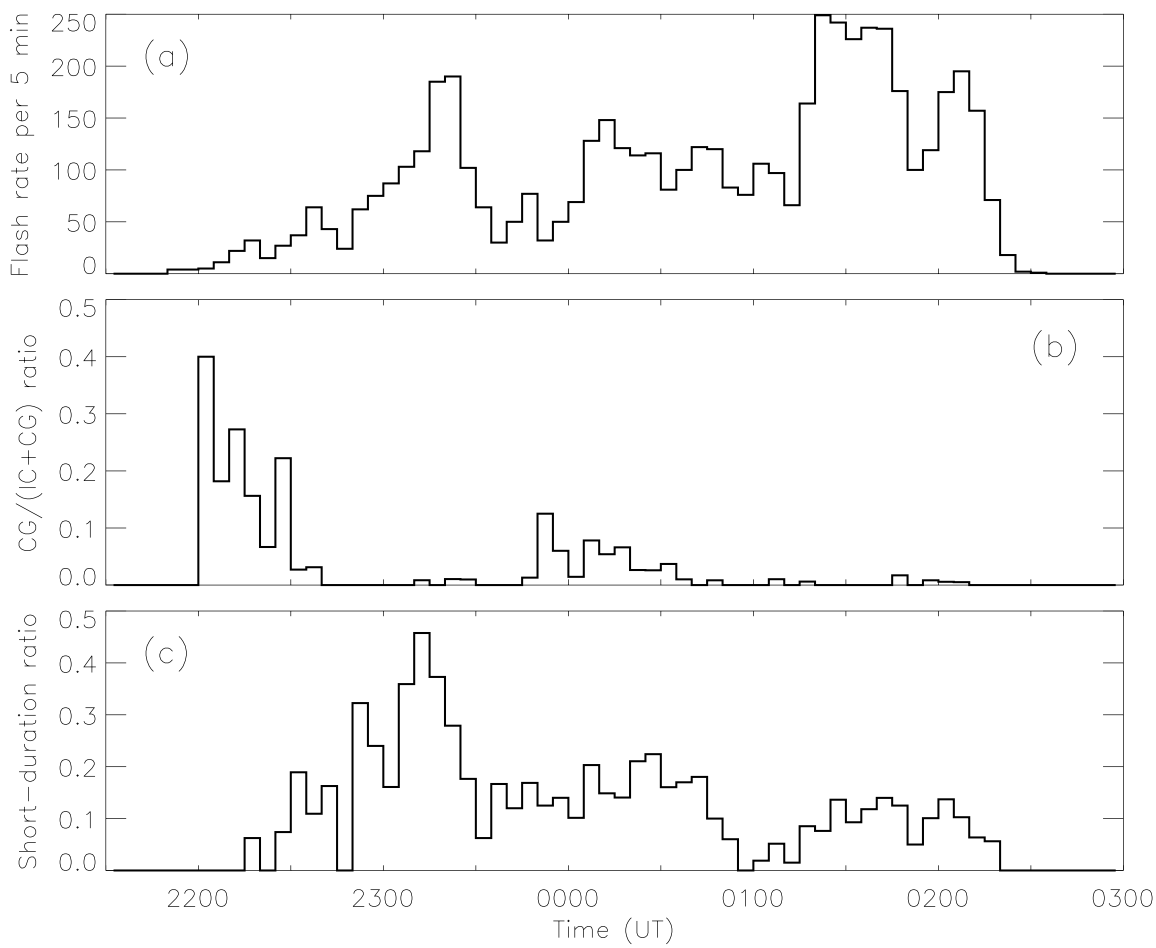

Flash rate per 5 min
250
200
150
100
50
0
(a)
CG/(IC+CG) ratio
0.5
0.4
0.3
0.2
0.1
0.0
(b)
Short−duration ratio
(c)
2200
2300
0000
0100
0200
0300
Time (UT)

Figure 6

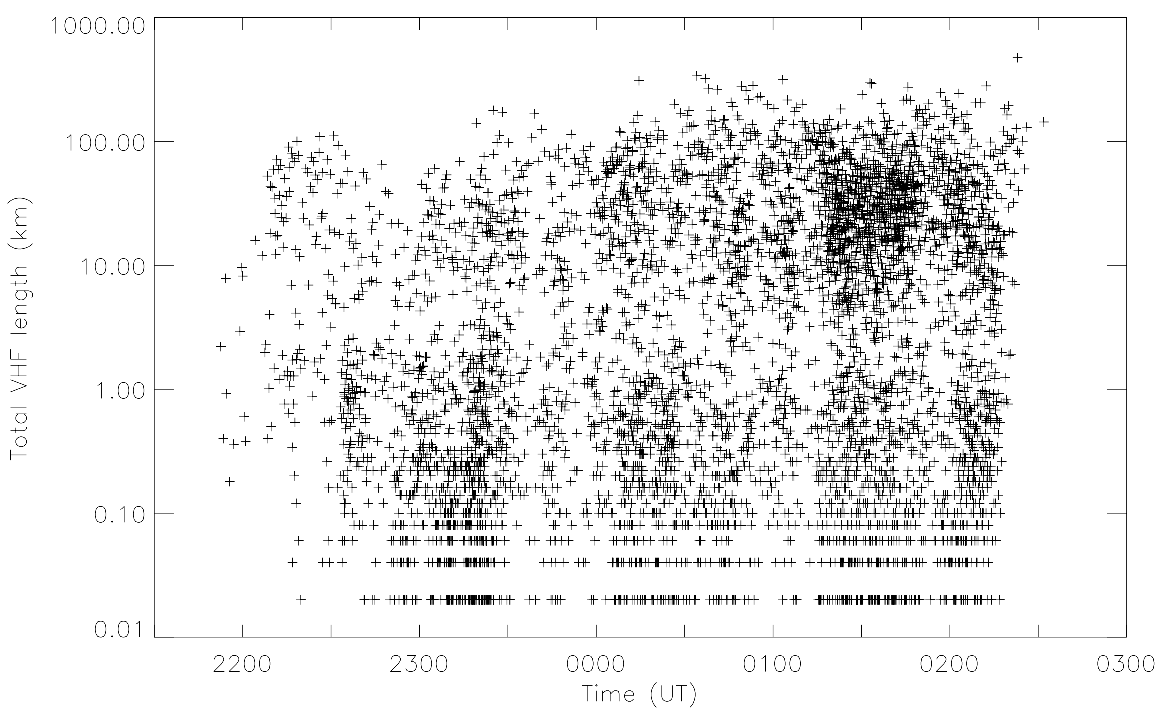

1000.00
100.00
10.00
1.00
0.10
0.01
Total VHF length (km)
2200
2300
0000
0100
0200
0300
Time (UT)

Figure 7

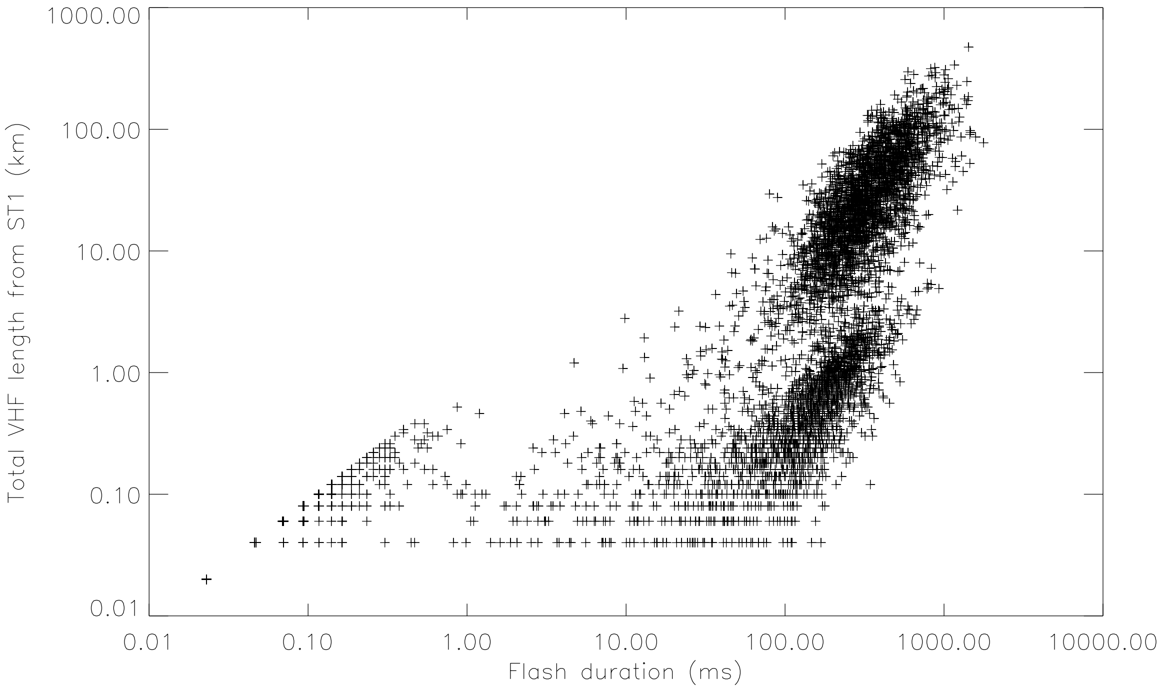
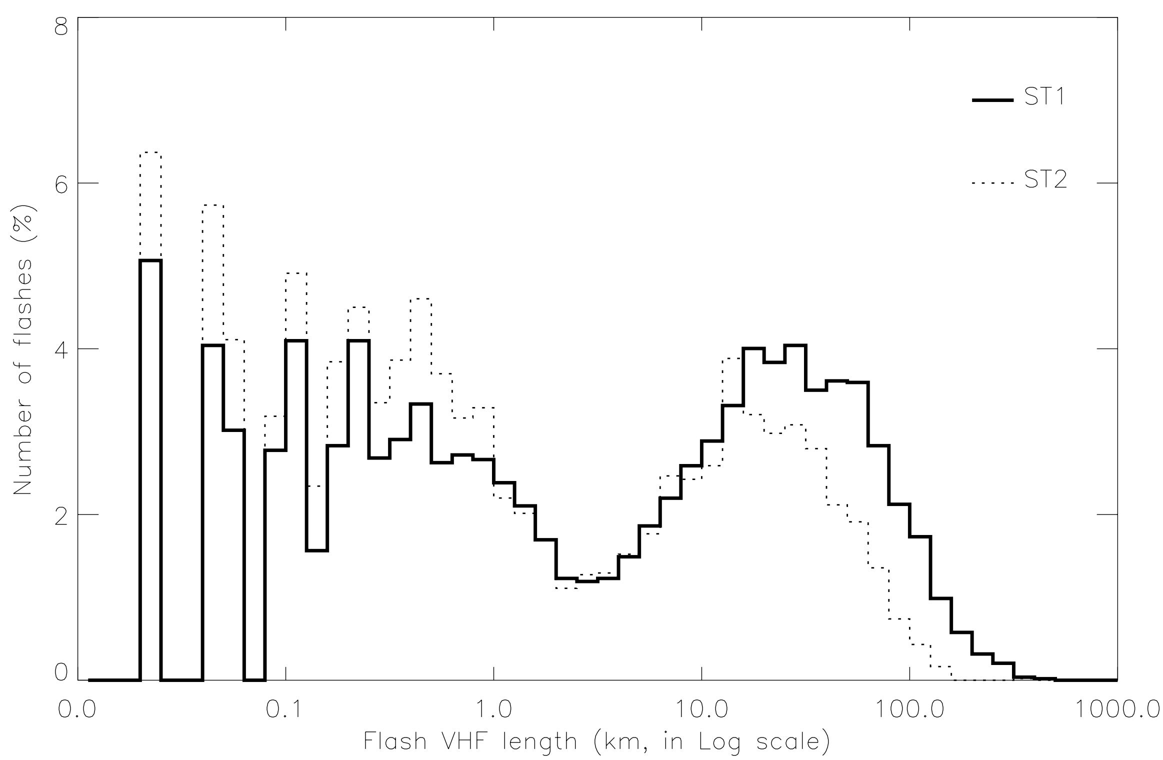
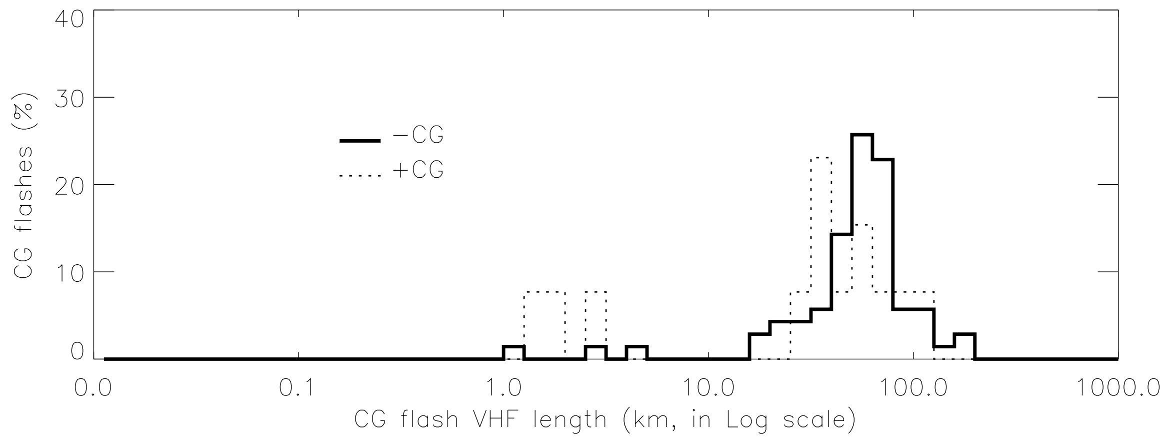

1000.00
100.00
10.00
1.00
0.10
0.01
Total VHF length from ST1 (km)
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Flash duration (ms)

Figure 8



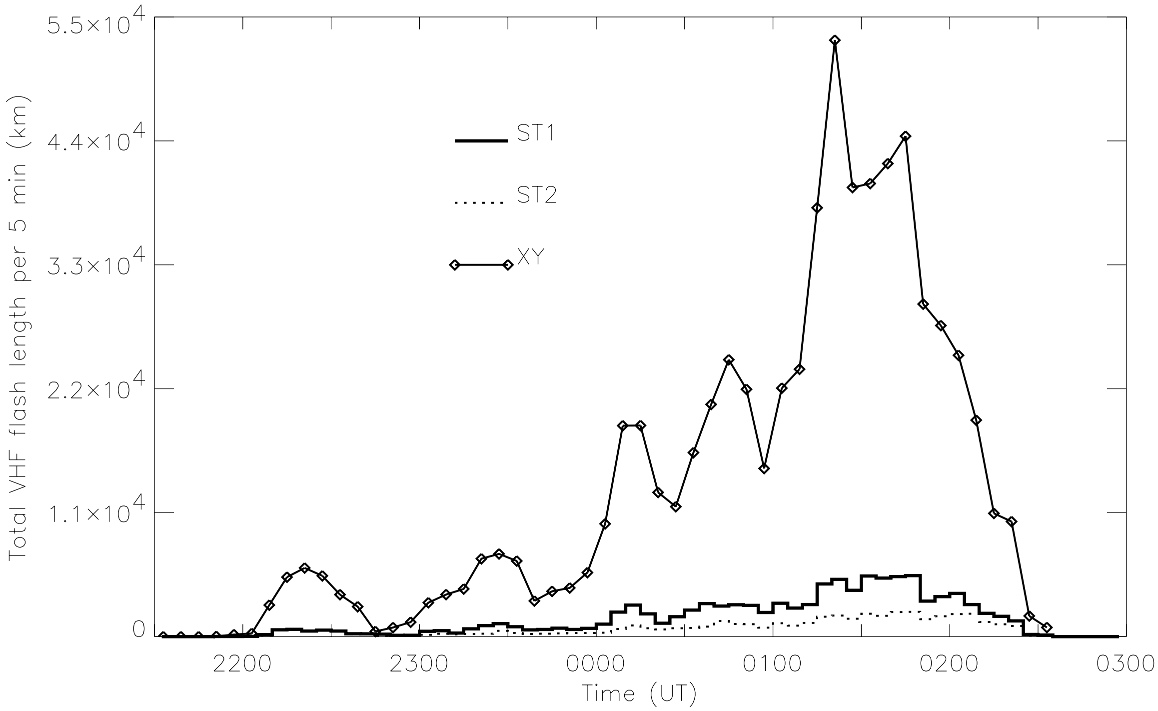
ST1
ST2
8
6
4
2
0
Number of flashes (%)
0.0
0.1
1.0
10.0
100.0
1000.0
Flash VHF length (km, in Log scale)

Figure 9



CG flashes (%)
40
30
20
10
0
−CG
+CG
0.0
0.1
1.0
10.0
100.0
1000.0
CG flash VHF length (km, in Log scale)

Figure 10



5.5×10^4
4.4×10^4
3.3×10^4
2.2×10^4
1.1×10^4
0
Total VHF flash length per 5 min (km)
ST1
ST2
XY
2200
2300
0000
0100
0200
0300
Time (UT)

Figure 11

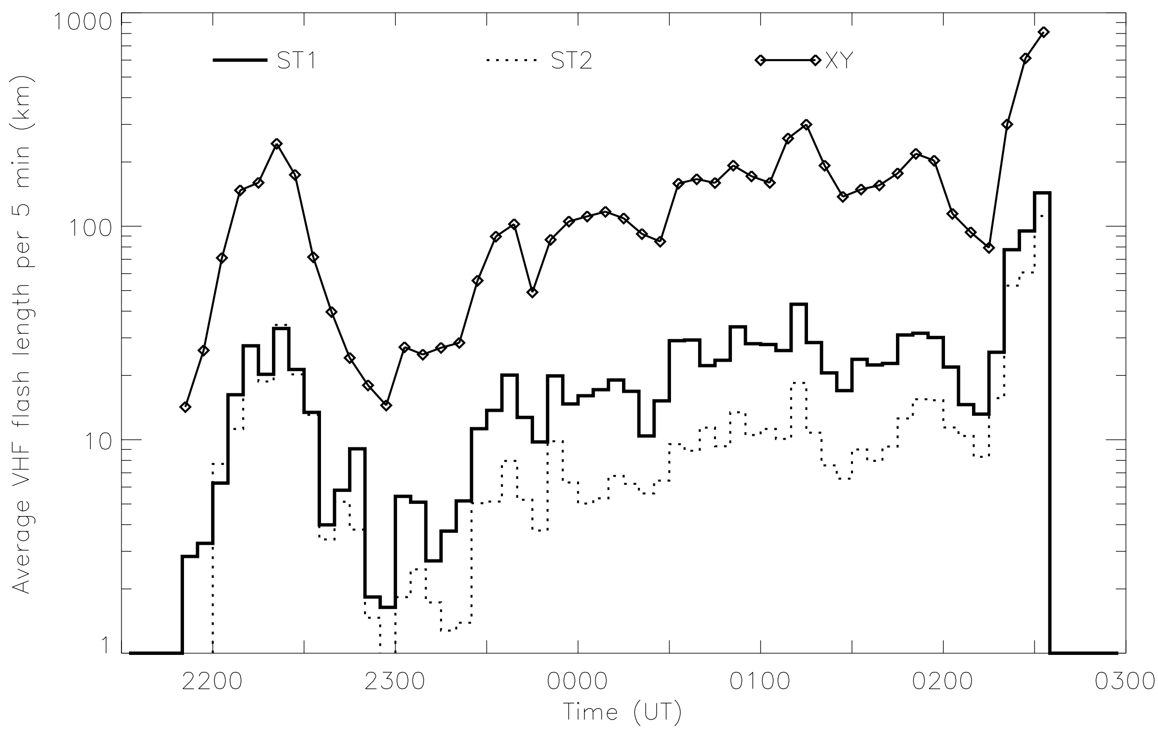

1000
100
10
1
ST1
ST2
XY
Average VHF flash length per 5 min (km)
2200
2300
0000
0100
0200
0300
Time (UT)

Figure 12

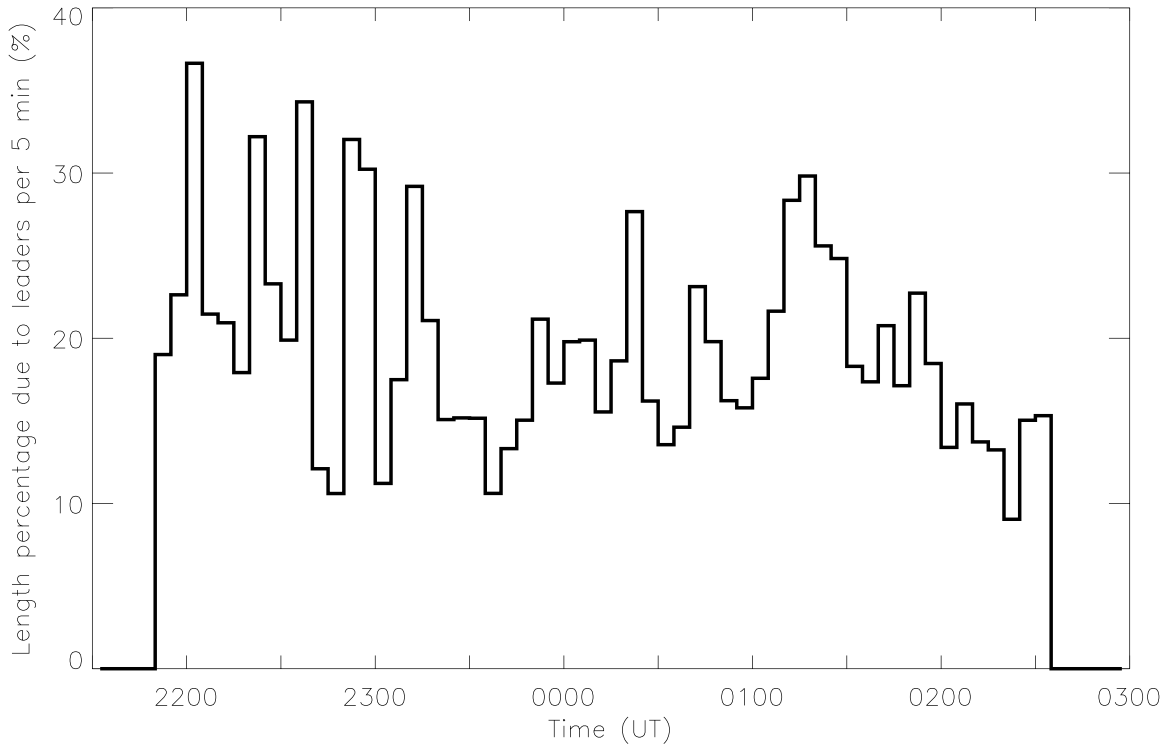

Length percentage due to leaders per 5 min (%)
40
30
20
10
0
2200
2300
0000
0100
0200
0300
Time (UT)

Figure 13