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LF/VLF and VHF Lightning Fast Stepped Leader Observations

Matthew J Heavner, David A Smith, Abram R Jacobson, and Ricki J Sheldon
Los Alamos National Laboratory

Abstract. This paper reports multi-platform observations of leader radiation preceding initial cloud-to-ground lightning return strokes by less than 6 ms. Specifically, we present multi-station ground-based VLF/LF recordings of events with large amplitude leader activity that is comparable in amplitude to the return stroke amplitude. The events were selected for their coincidence with VHF observations by the FORTE satellite. Some FORTE VHF leader step observations have obvious direct and ground reflection components. For these steps, which temporally correspond to specific features in the ground VLF/LF field change records, we calculate a source height based on event-satellite geometry. We determine source heights between 4.0 and 5.5 km. For FORTE records with multiple reflected events, we calculate vertical leader propagation velocities on the order of 10^6 m/s. The determined vertical leader propagation speeds are an order of magnitude greater than those reported as typical values for stepped leader velocities associated with initial return strokes.

Introduction

The transient electrical activity of thunderstorms (primarily due to return stroke and intracloud activity) generates electromagnetic radiation events known as atmosferics, or sferics. A typical return stroke produces radiation peaking in energy at a frequency of ~10 kHz [Volland, 1995]. Radiation at these frequencies propagates through the earth-ionosphere waveguide and can be observed at large distances (> 2000 km) from the source.

A negative cloud to ground lightning flash is often composed of multiple strokes. The initial stroke is preceded by a stepped leader that propagates downward from within the cloud at speeds on the order of 10^5 m/s. The velocity of a leader is a significant parameter of the electrical-breakdown process [Gallimberti, 1979].

When the attachment of the leader to ground occurs, a high current return stroke propagates back up the channel. Subsequent strokes in the same flash (generally within ~300 ms) usually have dart leaders or dart-stepped leaders that propagate down existing ionized channels at higher speeds on the order of 10^6 m/s and trigger a subsequent return stroke after ground attachment [Uman, 1987].

Schonland *et al.* [1938] reports electric field observations of two types of leader activity: α and β. The β leaders have initially-large amplitude electric field changes that coincide with bright optical emissions from the leader. Beasley *et al.* [1982] identifies the initial large-amplitude electric field change of β leader activity as being composed of 'characteristic pulses,' which are attributed to a transition between preliminary discharges and stepped leaders. Beasley *et al.* [1982] Figure 2b presents correlated observations of characteristic pulses in both VHF and broadband electric field records.

Proctor *et al.* [1988] provides a review of 13 studies reporting stepped leader propagation velocity. The range of velocities measured via photography, electric field change, 2-D interferometry, photoelectric, and hyperbolic radio (VHF time of arrival) studies is reported to be 2 x 10^4 to 7 x 10^6 m/s. The mean velocity of 66 events was 1.57 x 10^5 m/s. One "unusual lightning flash" described by Uman *et al.* [1978] was composed of three return strokes that "had unusually large peak currents and a stepped leader of relatively short duration," with a velocity of 2 x 10^6 m/s. Brook [1992] presents two electric field waveforms with intense leader radiation preceding an initial return stroke by less than 4 ms over winter thunderstorms. Ogawa [1995] presents four electric field waveforms showing lightning leader and return stroke features similar to those presented in this paper.

Los Alamos Sferic Array

The Los Alamos Sferic Array (LASA) is an array of electric field change meters that utilizes Global Positioning System (GPS) receivers to provide absolute event time tagging with an accuracy of better than 2 μs. The sensor response is relatively uniform over a bandwidth of 300 Hz to 500 kHz. The records discussed in this paper are 8 ms in duration and have been collected by a threshold triggering mechanism that includes 2 ms of pre-trigger data. In this paper, the trigger for described events was the leader radiation rather than the return-stroke.

During operations of the sferic array from 1998 through the present, stations have been located in New Mexico, Texas, Nebraska, Colorado, and Florida. The events in this paper were mostly recorded by the Florida stations. Smith *et al.* [2001] describe the operation and instrumentation of LASA and characterize the accuracy of LASA geolocation.

FORTE

The FORTE satellite was launched Aug. 1997 with instrumentation capable of making both Very High Frequency (VHF) and optical observations of lightning. The orbit altitude is approximately 820 km at an inclination of 70°. The FORTE VHF instrumentation consists of two tunable receivers with 22 MHz bandwidths and one tunable 85 MHz bandwidth receiver. The FORTE radio systems and typical observations are described by Jacobson *et al.* [1999]. The FORTE optical package consists of a fast, non-imaging photometer and a slower CCD array. The photometer has 15 μs sampling and a 80° field of view. The CCD, which provides lightning location to ~10 km spatial resolution, is queried every 2 ms, and the pixel location and value of every pixel with a value exceeding a noise riding threshold is recorded. The optical packages on FORTE are described by Suszcynsky *et al.* [2000].

Data and Analysis

The FORTE RF data are processed on the ground by applying spectral whitening (to remove anthropogenic noise, such as radio and television transmissions) and de-chirping (to remove ionospheric propagation effects) as described by Jacobson *et al.* [1999]. For some events, intermittent, narrow-band anthropogenic noise sources (*e.g.* radars) are removed via notch filtering.

Transient lightning emissions are often observed by FORTE as pulse pairs separated temporally by as much as 120 μs. These paired emissions were dubbed Trans-Ionospheric Pulse Pairs (TIPPs) by Massey and Holden [1995]. The pulse pairs often occur as a result of a direct and ground-reflected signal from an elevated discharge. The source altitude of the VHF radiation observed by FORTE is determined as described by Jacobson *et al.* [1999]. For the events presented in this paper, multiple height determinations are made in sub-millisecond time periods. A vertical velocity between each step is computed based on the height determined and the time delay between the onset of each pair. The errors associated with an accurate peak determination and errors in the height determination method lead to a velocity uncertainty less than 10%.

We present two detailed examples of leader radiation observed by FORTE RF sensors and the LASA electric field change sensors. The return stroke attachment is identifiable in both the FORTE and LASA records, so we use the return stroke as the fiducial point to eliminate the effects of any timing or location errors. In addition to calculating vertical velocities based on the leader steps, we calculate a propagation velocity based on the first determined height reaching the ground at the initiation of the return stroke.

July 11, 2000 16:20:39

The July 11, 2000 16:20:39.615019 UT event was recorded by four sferic array stations, two of which triggered on the leader radiation and two of which triggered on the return stroke. FORTE triggered twice during the 8 ms LASA record, collecting two 546 μs records. The first FORTE data collection was during the most intense leader radiation observed by the sferic array, and the second FORTE collection was during the return stroke. Figure 1 a is the 8 ms Kennedy Space Center (KC) waveform overlaid with the two 546 μs FORTE RF records. The FORTE records are scaled by 2.5 x 10^7 for comparison with the sferic array record. The zero time is based on the sferic array trigger point. The sferic array located the event at 26.94° N and -78.07° E,

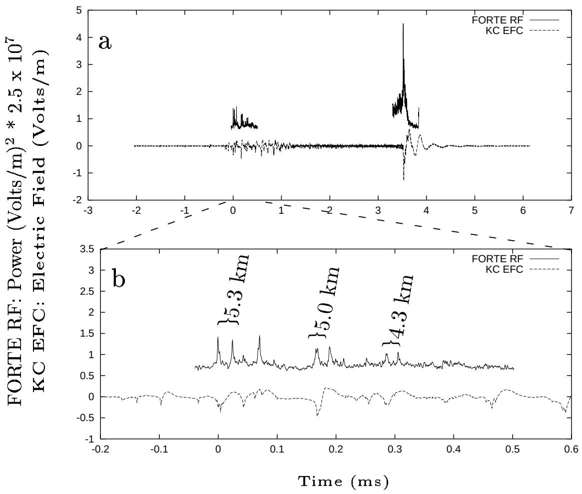

Figure 1. The July 11, 2000 16:20:39.612521 event. (a) An overlay of the 8 ms sferic array (VLF/LF) waveform and two 546 μs FORTE RF records. The FORTE collects were independently triggered. (b) An expanded view of the FORTE RF waveform and field change waveform with three pulse-pairs indicated. The three pulse pairs are determined to be from sources at altitudes of 5.2 km, 5.0 km, and 4.3 km. The delays between the pulse pairs are 166.4 μs and 119.3 μs which yield two values of vertical velocities: 1.7 x 10^6 m/s and 5.4 x 10^6 m/s or an average vertical velocity of 3 x 10^6 m/s.

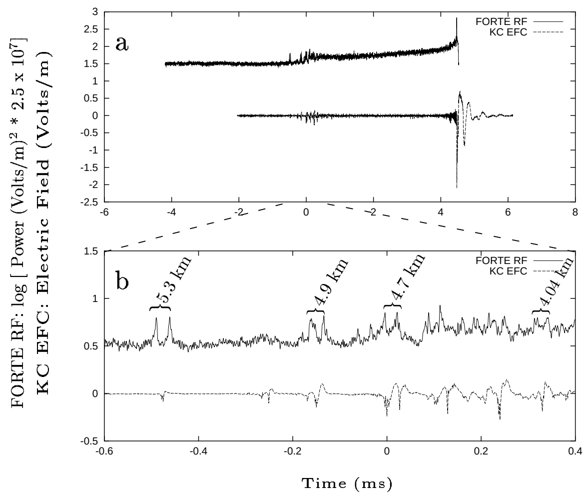

Figure 2. The August 19, 2000 event. (a) The 8 ms FORTE power vs time profile and the 8 ms Sferic Array VLF electric field waveform. (b) A 1 ms portion of the FORTE power vs. time profile showing the pulse pairs used to determine leader heights. The altitudes determined are 5.3 km, 4.9 km, 4.7 km, and 4.04 km. The vertical velocities computed by these three steps are 1.4, 0.88, and 2.1 x 10^6 m/s. The overall vertical velocity for the 804 μs duration of 4 pairs for which a height is determined is 1.6 x 10^6 m/s.

which is ~200 km east of the Florida coast, and a distance of 309 km from the KC station. Figure 1 b is an expanded view of the 546 μs plot of FORTE power associated with the leader activity. Three pulse pairs are identified. Based on the delay between the direct and reflected pulses, the source heights are 5.3 km, 5.0 km, and 4.3 km as indicated. Based on the time delays of 166.4 μs and 119.3 μs between the pairs of pulses, vertical velocities of 1.7 x 10^6 m/s and 5.4 x 10^6 m/s are determined. For the 285.7 μs duration across all three pulse pairs, the average velocity is 3.2 x 10^6 m/s. The FORTE RF power curve is consistent with the RF signature of an initial return stroke Suszcynsky *et al.* [2000].

August 19, 2000 08:00:15

A second example, from August 19, 2000 08:00:15, is presented in Fig. 2. This event was recorded by FORTE's 100 MHz bandwidth receiver with an 8 ms record length, while FORTE was operating with the optical systems as the event trigger source. Fig. 2 a presents the log of the full FORTE RF 8 ms power record and the 8 ms electric field change record. Beginning at approximately -0.5 ms, several pulse pairs are apparent in the FORTE RF record. The pairs are temporally coincident with strong leader pulses in the LASA record. After the pulse pairs, the overall RF levels increases by almost a factor of 5. Fig. 2 b shows a 1 ms section of the FORTE RF record with pulse pairs associated with strong leader activity. The heights determined by the pair separations and the satellite geometry are labelled. The heights determined are 5.3 km, 4.9 km, 4.7 km, and 4.0 km, with delays between each pair set of 326.5 ms, 159.6 ms, and 317.4 ms. These values give vertical velocities of 1.4 x 10^6 m/s, 0.88 x 10^6 m/s, and 2.1 x 10^6 m/s for each successive step, and an overall vertical velocity of 1.6 x 10^6 m/s. The vertical velocity based on a leader at the height determined for the first VHF pulse pair (5.3 km) reaching ground at the time of the return stroke (4.83 ms) is 1.1 x 10^6 m/s.

Discussion

We have presented ground-based VLF/LF and satellite-based VHF observations of unusual leader radiation.

Based on the VLF location of the event, we use the VHF observations to determine source altitudes of between 4.0 and 5.5 km within ∼4 ms before an initial negative return-stroke. Based on the altitude of multiple steps, velocities of 10^6 m/s are determined. The multiple-step velocity determination is consistent with the velocity required for the propagation of a leader from the initial height to the ground in the time between the initial leader and the return stroke. A total of four 'intense' or 'fast' leader/return stroke events observed by both FORTE and the sferic array have been identified. The average velocity of all events is 2.1 x 10^6 m/s with a range in velocities of 0.88 - 5.4 x 10^6 m/s.

One important issue regarding these observations is whether the observed leader is from an initial or subsequent return stroke (or a stepped leader or dart leader). Generally, initial return strokes generate the most intense electric field changes of a lightning flash [Rakov *et al.*, 1990]. The sferic array threshold triggering scheme causes stations to be most likely to trigger on and record intial return strokes. For the August 19, 2000 example presented, the FORTE photodiode record (not shown) corresponds to an initial negative return stroke, and the FORTE CCD location agrees with the sferic array determined location of 26.44 °N and -79.11 °E, east of the coast of Florida. FORTE observed this as part of a three stroke flash, in which this was the initial stroke. The sferic array electric field change record near the return stroke shows a relatively large amount of structure in the waveform which is strongly indicative of an initial return stroke as well. Based on both the FORTE and LASA observations, this event is indeed an initial negative return stroke. Of additional interest is that for the August 19, 2000 example, the FORTE RF observations confirm the return stroke to be a powerful, narrow negative attachment over seawater as described by Jacobson *et al.* [2001].

One of the original sources of motivation for this study was a paper published by Brook [1992] that proposed that intense/fast leader radiation occured over only winter thunderstorms. In contrast to this conclusion, the two examples presented here are both from summer thunderstorms. One FORTE/sferic array coincident observation of similar leader radiation occurred on October 4, 2000. All of the FORTE/LASA leader events identified to date occurred over seawater, but other sferic array observations of similarly intense leader activity associated with an intial return stroke have been located well within land masses (*e.g.* central New Mexico).

We have presented two examples of strong leader radiation recorded by the Los Alamos Sferic Array with coincident FORTE RF observations. We are developing a database of leader radiation observed by the sferic array that will allow us to perform a statistically significant study of electric field changes associated with leader activity. The database will cover the four years of sferic array observations and should have approximately 300,000 leader events recorded at multiples stations. Once this leader database is completed, the occurrence rate of this intense leader radiation which is associated with fast leader propagation will be determined. However, the large majority of these leader waveforms will not have coincident FORTE events, so the height/velocity calculations presented in this paper will not be possible.

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MJ Heavner, Space and Atmospheric Sciences Group, NIS-1, MS D466, Los Alamos National Laboratory, Los Alamos NM 87545. heavner@lanl.gov

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