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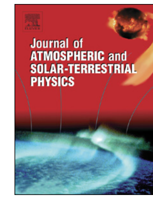

Characteristics of negative lightning leaders to ground observed by TVLS

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A B S T R A C T

The Thunder and VHF lightning Locating System (termed TVLS) is established and utilized to observe leader behaviors of negative cloud to ground (CG) flashes. This system takes advantages of VHF broadband interferometer and thunder imaging technique, which could provide the temporal and quasi-3D spatial evolution of lightning discharges. In conjunction with synchronized electric field changes (*E*-changes) and electric field derivatives (d*E*/d*t*) records, 10 leaders from two CG flashes are presented and analyzed. Based on the characteristic evolution of leader velocities, *E*-changes, d*E*/d*t* waveforms and VHF intervals, three stepped leaders, five dart leaders and two dart-stepped leaders are identified. The stepped leaders behave impulsive while approaching ground, with average speed $(1.3{\sim}3.9)\times 10^5$ m/s. All normal dart leaders presented here exhibit irregular (or termed “chaotic”) fluctuations in *E*-change and d*E*/d*t* waveforms, with the similar speeds $((1.0{\sim}2.9)\times 10^7$ m/s) and durations ((300~700) μs) of the “chaotic” leaders observed by other investigators. The irregular fluctuations would be weak if the channels keep conductive until the leader enters the less conductive branches, coinciding with VHF radiations in time sequence. The dart-stepped leader could be divided into the dart stage and the stepped stage by a transition region, which usually lies around the branch junctions of previous active channel. The dart stage resembles the normal dart leader, and the stepped stage usually associates with regular pulse trains in *E*-change and d*E*/d*t* waveforms.

1. Introduction

Understanding lightning leader processes is a key for lightning protection, and provides an effective way to reveal physical mechanism of lightning discharges. Based on the electric field change (*E*-change) characteristics, the common negative lightning leaders are usually divided into three types: stepped leader, dart leader and dart-stepped leader (Krider et al., 1977). Stepped leader occurs preceding the first return stroke, while dart leaders usually follow the previous established lightning channels (Rakov and Uman, 2003). If the dart leader enters a channel less conductive, it may evolve to dart-stepped leader (Uman, 2001).

Lightning leaders to ground have been investigated by number of researchers in the past decades. Especially recently, benefited from the highly time-resolved imaging techniques, lightning leaders have become a renewed interest. Fine structures in evolution characteristic and formation mechanism of lightning leaders have been gradually revealed (Biagi et al., 2014, 2010; Edens et al., 2014; Gamerota et al., 2014; Hill et al., 2012; Jiang, et al., 2014; Stolzenburg et al., 2014) and some new leader types are also identified (Campos et al., 2014; Stolzenburg et al., 2013). However, there are still some unresolved questions in leader propagations, such as: what happens in “chaotic” dart leader? How does a leader evolve to a dart-stepped leader or stepped leader? And what is the relation among *E*-change, EM radiations and developing behavior in different leader processes?

VHF mapping technique provides another valuable tool to study leader breakdown processes. Moreover, VHF receivers could retrieve the sources obscured by clouds, which may not be “seen” by video observations. In this work, the comprehensive Thunder and VHF lightning Locating System (termed “TVLS”) synchronized with *E*-change and electric field derivatives (d*E*/d*t*) was utilized to study the different behaviors of negative lightning leaders to ground, and the finding on the physics of dart leader propagation was also discussed.

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2. Experiment setup and methodology

The proposed observation system TVLS takes advantage of thunder imaging and VHF broadband interferometer to retrieve the evolution of the radiation sources with quasi three dimensional (3D) locations. Moreover, the synchronized E-changes and dE/dt signals are recorded to analyze leader propagations in a more comprehensive view.

2.1. Instrumentation

The configuration of TVLS antenna is illustrated in Fig. 1. A perfectly matched VHF and acoustic receiver array consists of three horizontally separated units. The three units aligned at three apexes of a square with the baseline's length of 12.5 m. Each unit is composed of a VHF broadband antenna and a high-gain capacitor microphone. Broadband VHF radiations (30–300 MHz) are band-stop (88–108 MHz) filtered and then digitized at a rate of 1GS/s with 8 bit resolution by a digital storage oscilloscope (DSO). The whole memory of DSO is divided into numbers of segments, with each segment recording several microseconds, and each segment is triggered independently when the VHF radiation exceeds the defined threshold. The dead time between segments is less than 1 μs. Three microphones are connected to a PCI data acquisition card, with sampling rate at 100 kS/s and duration of 30 s. In addition, a PCI data acquisition card operates with sampling rate at 10 MS/s is synchronized to record E-changes (with decay time constant of 1 ms) and dE/dt radiations. Data acquisition of the system is triggered by VHF signals, and the whole TVLS system is automatically controlled by the PC-based program to ensure all records are synchronized in time.

2.2. Quasi-3D localization

In order to retrieve the three dimensional (3D) development of leader processes, a joint localization methodology which combines broadband interferometry and thunder imaging techniques is introduced (Qiu et al., 2012). The outline of the localization procedure could be generalized as the following three steps:

(1) The azimuth and elevation of VHF and thunder sources could be resolved by broadband interferometry (Qiu et al., 2009) and acoustic ray tracing (Few, 1970) techniques respectively;

(2) Thunder sources have additional range information by measuring the differential time of arrival (DTOA) between thunder and lightning electromagnetic pulse (LEMP);

(3) Thunder sources have a matched azimuth and elevation with VHF sources could provide a quasi-3D VHF imaging.

Considering that the same geometry configuration is used in both the VHF and acoustic array, localization discrepancy arisen from array installation would be minimized. In order to further evaluate the location uncertainty of TVLS, a rough estimation method is proposed here.

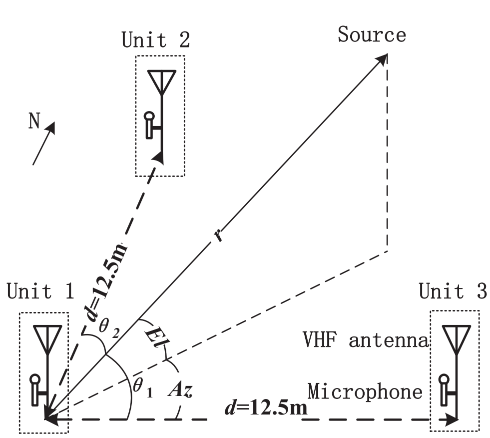

Fig. 1. Layout of the VHF and acoustic array in TVLS.

The 3D location uncertainty (U_p) for position P consists of two components: radial uncertainty (U_{rad}) and tangential uncertainty ($U_{\tan}$). Radial uncertainty can be attributed to acoustic velocity changes and the DTOA uncertainty (δ_t) between thunder signals and LEMP. Usually, err caused by acoustic velocity changes could be neglected compared to the DTOA uncertainty, and the later arises from the time-window duration for retrieving a thunder source. In the present work, the 100 ms time-window is adopted, which means that the DTOA uncertainty for each source is 50 ms. Tangential uncertainty is in proportion to the angle uncertainty (δ_θ). For the presented 10 leaders, angle differences from thunder sources to the closest VHF sources are less than 2°, so it is reasonable to infer that the angle uncertainty (δ_θ) is less than 1°. In summary, 3D location uncertainty (U_p) of the system could be derived by Eq. (1), where v represents acoustic velocity and r represents the radial distance from observation site to the source.

$$U_p = \sqrt{U_{\text{rad}}^2 + U_{\tan}^2} = \sqrt{(v \cdot \delta_t)^2 + (r \cdot \delta_\theta)^2} \tag{1}$$

2.3. 3D velocity estimation for leaders

Since quasi-3D locations of leaders were available, the velocity variations during their development could be derived by the following steps:

(1) Dividing the channel into $(N-1)$ piecewise linear segments by N sources which located at $_{Pi}$, $i=1, 2, \ldots, N-1$;

(2) Calculating the length of each segment (l_i) between two adjacent points $_{Pi}$ and $_{Pi+1}$;

(3) Obtaining the time duration (Δt_i) when the leader passes through each segment by VHF results, and thereafter, the leader velocity during each segment could be derived by Eq. (2), and the mean velocity over $(N-1)$ segments could also be deduced by Eq. (3).

$$v_i = \frac{l_i}{\Delta t_i} = \frac{|P_{i+1} - P_i|}{\Delta t_i}, \quad i = 1 \cdots N-1 \tag{2}$$

$$\bar{v} = \frac{\sum_{i=1}^{N-1} l_i}{\sum_{i=1}^{N-1} \Delta t_i} = \frac{\sum_{i=1}^{N-1} |P_{i+1} - P_i|}{\sum_{i=1}^{N-1} \Delta t_i} \tag{3}$$

The velocity uncertainty corresponding to Eqs. (2) and (3) are given by Eqs. (4) and (5), respectively. Note that the uncertainty of Δt_i is too small to be neglected compared with the length uncertainty (U_{li}).

$$U_{v_i} = \frac{U_{l_i}}{\Delta t_i} = \frac{\sqrt{U_{P_{i+1}}^2 + U_{P_i}^2}}{\Delta t_i}, \quad i = 1 \cdots N-1 \tag{4}$$

$$U_{\bar{v}} = \frac{\sqrt{\sum_{i=1}^{N-1} U_{l_i}^2}}{\sum_{i=1}^{N-1} \Delta t_i} \tag{5}$$

3. Observations

In the summer of 2011, a comprehensive lightning observation was conducted using the TVLS in Nanjing, China. 10 Leaders from two negative natural cloud-to-ground (CG) flashes are analyzed in this work. Since TVLS system could provide quasi-3D development of leaders as well as strictly synchronized E-changes and dE/dt