On the VLF/LF Radiation Pulse Shapes at the Initial Milliseconds of Lightning Discharges

Xuan-Min Shao[1] and Matthew Heavner[2]

[1]Space and Remote Sensing Sciences, Los Alamos National Laboratory, New Mexico, USA
[2]Department of Natural Science, University of Alaska Southeast, Juneau, Alaska, USA.

Abstract — **This report examines the shape and amplitude of the VLF/LF radiation pulses within the initial milliseconds of lightning discharges. A simple model regarding the discharge process and channel condition is proposed to compute the radiation pulses. With some reasonable assumptions regarding the current propagation speed and the current damp length, the modeled pulses are in good agreement with the observations. Based on our analysis, we infer that lightning channel becomes increasingly active during the first hundreds of μs and then becomes continuously less active thereafter.**

I. INTRODUCTION

Electric field observations at very low frequency (VLF) and low frequency (LF) has been used for decades to study lightning discharges. Observations at these frequencies provide the fundamental information on the lightning types and signatures. Pulse shapes of VLF/LF lightning signals have been intensively examined for return stroke, stepped leader, K-change, and other types of lightning discharge processes. Even with modern lightning research and operational technologies, such as VHF lightning geolocating systems, satellite optical and radio frequency (RF) lightning sensors, electrical field change at VLF/LF still plays the fundamental role on identifying the discharge processes that are observed by the other means, and helps to understand the physical nature of the corresponding observations.

In this report, we focus on the VLF/LF pulse shapes that are observed at the initial milliseconds of intracloud (IC) and cloud-to-ground (CG) lightning discharges, when the discharges are distant from the sensor. For distant lightning the received signals are predominately associated with the radiation component of the total field, which simplifies the analysis.

Figures 1a and b show the radiation pulses at the initial milliseconds of an IC and a -CG discharge respectively. The data were recorded by field change sensors of the Los Alamos Sferic Array (LASA) [Smith et al., 2002, Shao et al., 2005] that are deployed in the Great Plains states and in Florida. LASA has been used to provide ground-truth measurement for Los Alamos National Laboratory's satellite programs. The sensors operate at the frequency range of 200Hz-500 kHz with a RC time constant of ~1 ms. The IC discharge (Figure 1a) was 125 km from the sensor, as geolocated by the array, and the –CG (Figure 1b) was 192 km from the sensor. The IC radiation pulses are positive in polarity due to the apparent upward movement of negative charge, and the –CG pulses are negative due to the downward movement of negative charge. Despite the opposite polarity between the two pulse sequences, we notice that the pulses are typically bipolar at the early times, and gradually become unipolar as the discharges develop, as shown by the zoomed-in pulses. We also notice that, in general, the biggest pulses appear at the very early stage after one or a few small pulses, and the pulses become increasingly smaller while they change from bipolar to unipolar. Similar pulse sequences are not uncommon in either our own database or in other researchers' published field change waveforms [e.g., Brook, 1992, Heavner et al., 2002].

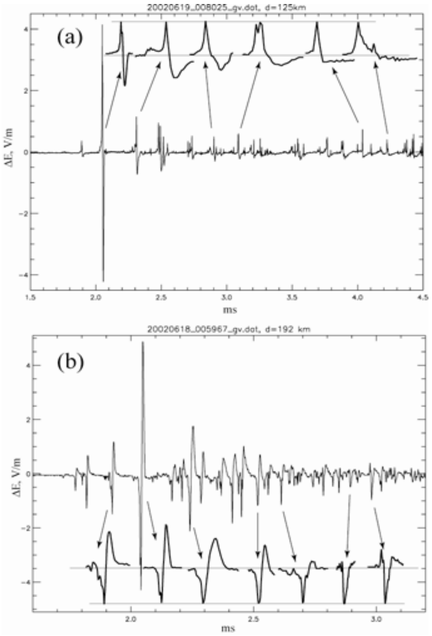

Fig. 1. Pulse sequences at the initial milliseconds of IC (a) and –CG (b) discharges.

The question is: what can these pulses tell us regarding the physical nature of the discharge process, especially at the initial stage of a lightning flash? In this report, we attempt to look for some possible explanations for the pulse shapes, and then explore the consequent implications to the understandings of the physical processes

II. ANALYSIS

To examine the pulse shape, we require a discharge model that is responsible to the electromagnetic radiation.

We assume that each pulse is associated with a discharge event at the head of an extending channel. The discharge injects a current pulse that propagates backward into the trailing channel. As the current propagates, its amplitude is assumed damped continuously, same as that in the modified transmission line model (MTL) proposed by Nucci et al. [1988] for a return stroke.

For the MTL current model, i.e., $i(z',t') = i(0,t'-z'/v)e^{-z'/\lambda}$, where z' is the spatial coordinate along the channel, starting from the channel head, t' is the retarded time, v is the propagation speed, and λ is the 1/e damp length in the stationary coordinate frame, the radiation field in frees pace can be expressed as, according to Shao et al., [2004, 2005],

$$\boldsymbol{E} = \frac{1}{4\pi\varepsilon_0 c^2 r}\frac{v\sin\theta\hat{\boldsymbol{a}}_\theta}{(1-v\cos\theta/c)}\left[i(0,t') - \frac{1}{\lambda'}\int_0^{L'} i(0,t'-z'/v)e^{-z'/\lambda'}dz'\right] \tag{1}$$

Here, $\lambda' = \lambda(1 - v\cos\theta/c)$ for $\lambda << r$, the apparent damp length viewed from a moving frame that travels along with the current pulse; $L' = vt'$ is the effective channel length; c is the speed of light; θ is the angle between the channel and the line of sight; and r is the distance from the channel to the sensor. For the analysis in this report, the channel at the initial milliseconds can be assumed vertical, and for a distant sensor, θ equals $\pi/2$. Including the ground effect, the radiation field is then

$$E_z = \frac{v}{2\pi\varepsilon_0 c^2 r}\left[i(0,t') - \frac{1}{\lambda}\int_0^{L'} i(0,t'-z'/v)e^{-z'/\lambda}dz'\right] \tag{2}$$

for a sensor on the ground.

Using Eq. 2 and a Gaussian shape for the current pulse (Figure 2a), the radiation pulse shape is found to be dependent on (1) the damp length, (2) the propagation speed, and (3) the duration of the current pulse, as shown in Figures 2b, c, and d, respectively. With longer damp length, the radiation pulse becomes more unipolar and greater in amplitude. At greater propagation speed, the radiation pulse becomes more bipolar but greater in amplitude. For longer current pulse, the radiation becomes more bipolar and smaller in amplitude. It is clear that each of the three parameters can affect the relative radiation pulse shape between bipolar and unipolar, with the other two parameters stay unchanged.

We now examine the physical implication of the parameters and try to find out which parameter may dominate the process. If the damp length increases as discharge develops, the trailing channel would have to be more and more conductive. A more conductive channel will in turn enables faster current propagation [Borovsky, 1995]. The combination of these two factors will increase the pulse amplitude monotonically with time and the pulse shape will stay more or less the same bipolar shape. The pulse series prior to the biggest pulse in Figure 1b appear to fall into this situation. The pulses after the biggest pulse in both Figures 1a and b do not indicate an increasing damp length. On the other hand, if the channel decays continuously following the biggest radiation pulse, the current propagation speed will be continuously reduced and the damp length will be continuously shortened. In this case, the radiation pulse will become smaller and smaller, and depending on the relative rate of change between the two parameters, the pulse shape could become more asymmetric (or unipolar), agreeing with the general trend of the observed pulse sequences following the largest amplitude pulse.

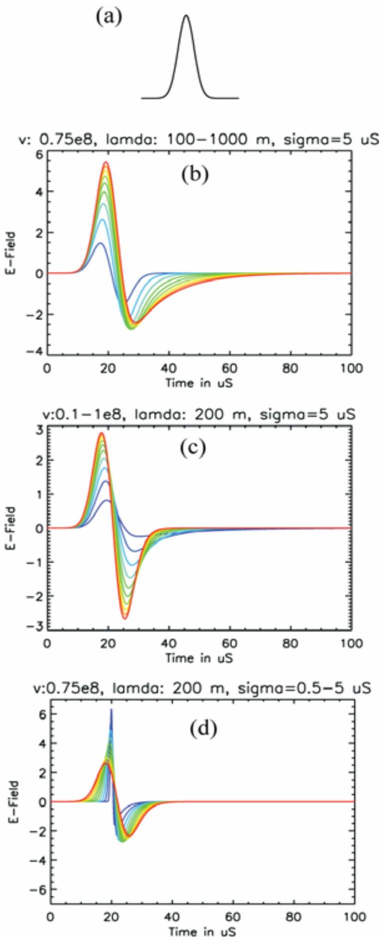

Fig. 2. (a) Injected current pulse. (b) Radiation pulse shape as function of damp length, from 100m (blue) to 1 km (red). (c) Pulse shape as function of current propagation velocity, from 0.1 to 1×10^8 m/s (blue to red). (d) Pulse shape as function of current pulse width, from 0.5 to 5 μs (blue to red).

Figure 3c shows the simulated results based on the above discussion. Without direct measurement of the current propagation speed, we hypothesize the speed to be between those of return stroke (10^8 m/s) and dart leader (10^6 m/s), and assume the speed increases at the first sub-millisecond stage and then decreases afterward (Figure 3b). Similarly, there exist no measurement on the current damp length, but it is reasonable to assume a range of 10s to 100s meters, based on photographic observations of stepped leader processes when the leader descends below the cloud base. Again, the damp length is assumed increasing at the first stage and then decreasing thereafter, corresponding to the change of the current speed. To best fit the measurements, the speed is assumed to decrease at a faster rate then the shortening of the damp length, which may indicating some physical significances of the channel dynamics and requires further investigations.

In Figure 3c, the time interval between the successive pulses is assumed a constant 300 μs, which corresponding to a channel extension speed of 2×10^5 m/s, in general agreement with the observed leader speed at the initial stage of lightning discharges [Shao and Krehbiel, 1996, Behnke et al., 2005]. The pulse shape and amplitude follow the general trend of that in Figure 1, suggesting that the model analysis reflects the actual discharge and channel properties. To compare to the –CG pulses, the polarity in Figure 3c only needs to be reversed.

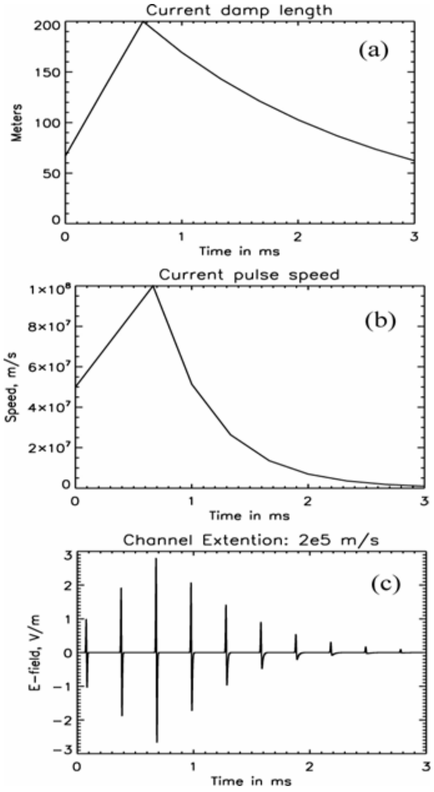

Fig. 3. Assumed current damp length (a) and propagation speed (b) as function of time. (c) Computed pulse sequence.

The first pulse Figure 1a as well as some small and narrow pulses across the records is more unipolar than bipolar, seemly to disagree with the modeled result. We explain this disagreement by the results of Figure 2d. For a narrow current pulse, the radiation pulse intends to be more unipolar under the same channel conditions.

III. SUMMARY

This report presents a simple discharge model to simulate the VLF/LF radiation pulses in the initial milliseconds of lightning discharges. The model appears capable of explaining the observed development of the pulse shape and amplitude with reasonable assumptions. If the model indeed reflects the actual properties of the discharge process and the channel dynamics, it indicates that the lightning channel becomes increasingly active during the first few hundreds of μs, and then decays thereafter. Behnke et al. [2005] recently reported that the leader speed of intracloud lightning decreased in the initial ~10 ms and inferred that the channel became increasingly less active during this time interval. Our analysis agrees with Behnke et al. after the biggest radiation pulse. Due to the lack of temporal and spatial resolution, Behnke et al. [2005] were not able to detect the speed behavior within the first millisecond, but proposed a pre-conditioned conducting channel before the VHF sources detected by their Lightning Mapping Array (LMA). Analysis reported here appears to suggest that the channel is less conductive at the very beginning but it quickly becomes conductive in a few hundreds of μs.

ACKNOWLEDGEMENT

This work was supported by the US Department of Energy.

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