Lightning Properties Inferred from Measurements of Very Close Electric Fields

V. Kodali, V.A. Rakov, M.A. Uman, K.J. Rambo, G.H. Schnetzer, J. Schoene, D.E. Crawford

Department of Electrical and Computer Engineering
University of Florida, Gainesville

ABSTRACT: Lightning properties including dart-leader charge density, return-stroke propagation speed, dart-leader electric potential, and dart-leader propagation speed, inferred from current and close electric field measurements are presented. Although all estimates presented here are based on rather crude models, they are generally in remarkably good agreement with independent measurements and/or theoretical considerations found in the literature. The results are applicable to rocket-triggered lightning strokes and probably to subsequent strokes in natural lightning. Additionally, we present evidence that larger return strokes can leave appreciable unneutralized charge near ground.

INTRODUCTION

We used close electric field and associated channel-base current measurements for rocket-triggered lightning (i.e., Rakov et al. 1998) to infer various properties of lightning discharges, including (1) dart-leader charge density, (2) return-stroke propagation speed, (3) dart-leader electric potential, and (4) dart-leader propagation speed. Although the analysis is based on simple models, the results are generally similar to those obtained from independent measurements and/or expected from theoretical considerations. Additionally, electric field waveforms due to dart leader/return stroke sequences at 15 and 30 m are examined for the so-called residual electric field which is presumably associated with leader charge left unneutralized near ground by the return-stroke process.

The measurements were made at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, in 1999, 2000, and 2001. The instrumentation and experimental set-up used at the ICLRT in these years are described by Crawford et al. (2001), Rakov et al. (2001), Uman et al. (2002), Schoene et al. (2003), and Kodali (2003). Triggered-lightning strokes are similar to subsequent strokes in natural lightning. Therefore, the results presented in this paper are likely to apply to subsequent strokes in natural lightning.

LEADER CHARGE DENSITY

As shown by Rubinstein et al. (1995), the vertical electric field change $\Delta E_L$ due to a uniformly charged leader at a very close distance $r$ can be expressed as

$$\Delta E_L = \frac{\rho_L}{2 \pi \varepsilon_o r}$$  \hspace{1cm} (1)

where $\rho_L$ is the line charge density on the leader channel and $\varepsilon_o = 8.85 \times 10^{-12}$ F/m. Further, Crawford et al. (2001) inferred a more or less uniform distribution of charge along the bottom kilometer or so of the dart-leader channel in rocket-triggered lightning. We used values of $\Delta E_L$ measured at $r = 15$ m and $r = 30$ m at the ICLRT in 1999-2001 and Eq. 1 to estimate the corresponding values of $\rho_L$. The results are presented in Figs. 1a and 2a. For all data combined, the mean values of $\rho_L$ from the electric field measurements at 15 and 30 m are 98 and 101 $\mu$C/m, respectively. The overall range of variation is from 26 to 210 $\mu$C/m. The values of $\rho_L$ are used below for estimating electric potential of the dart-leader channel.

RETURN-STROKE PROPAGATION SPEED

We obtained estimates of the return-stroke speed as $v_{RS} = I/\rho_{RS}$ where $I$ is the return-stroke peak current and $\rho_{RS}$ is the line charge density along the return stroke channel. The latter can be found from measured close electric field change $\Delta E_{RS}$ due to the return stroke as $\rho_{RS} = 2 \pi \varepsilon_o r \Delta E_{RS}$ (Thottappillil et al. 1997). Since this equation for speed is valid only when the return-stroke current is a step-function wave propagating along the channel at a constant speed, our speed values are very rough estimates. The results are shown in Figs. 1b and 2b. For all data combined, the mean values estimated using field measurements at 15 and 30 m are $1.9 \times 10^7$ and $1.6 \times 10^7$ m/s, respectively. The overall range of variation is from about $3 \times 10^7$ to $2.7 \times 10^8$ m/s. The estimated speed values are consistent with optical measurements (see Rakov et al. 1992 for a review).

DART-LEADER ELECTRIC POTENTIAL

Electric potential of the lightning leader channel can be estimated as $V = \rho_L/\epsilon$ where $\rho_L$ is the line charge density on the leader channel and $C$ is the capacitance per unit length of the channel. Values of $\rho_L$, for the bottom kilometer or so of the lightning channel were computed from measured close leader electric field changes, as discussed above, and $C$ was found as

$$C = \frac{2 \pi \varepsilon_o}{\ln (2h/r)}.$$  \hspace{1cm} (2)

A similar approach to estimating the potential of stepped leaders in natural lightning was used by Mazur and Ruhnke (2002). In equation 2, $r$ is the radius of the leader channel (not to be confused with the horizontal distance from the
lightning channel in Eq. 1) and \( h \) is the height above ground. Clearly, \( C \) decreases with increasing \( h \), although the variation is slow (logarithmic). In using Eq. 2, we assumed that \( r = 2 \) m (taking into account the radial corona sheath surrounding the channel core and containing the bulk of the leader charge) and that \( h = 500 \) m (midpoint of the bottom kilometer of the channel considered here). The resultant value of \( C \) is 8.9 \( \mu \text{F/m} \). In this simplified approach, the leader channel potential is proportional to the measured leader electric field change. The results are presented in Figs. 1 and 2c. For all data combined, the mean value of leader potential is 11 MV (the same for 15-m and 30-m field measurements), with the overall range of variation being from about 3 to 24 MV. The estimated values of electric potential are consistent with the 15 MV value inferred for subsequent strokes by Rakov (1998).

DART-LEADER PROPAGATION SPEED

For a uniformly charged leader, one can find from electrostatic considerations the height \( H \) of the descending leader tip above ground at the time of maximum leader \( \text{dE}/\text{dt} \) at distance \( r \): \( H = r \sqrt{2} \). Further, the time required for the leader to propagate from height \( H \) to ground can be found by measuring the time interval \( T_L \) between the leader \( \text{dE}/\text{dt} \) peak and the \( \text{dE}/\text{dt} \) zero crossing, as described by Rakov et al. (2000). We used dart-leader \( \text{dE}/\text{dt} \) signatures recorded at \( r = 15 \) m (such signatures at \( r = 30 \) m were generally unpronounced) to measure \( T_L \) and then computed leader speeds as \( v_L = H/T_L \). The results are shown in Fig. 1d. For all data combined, the mean value of speed is 7.5 \( \times 10^7 \) m/s with the overall range of variation being from 2.0 \( \times 10^7 \) to 1.5 \( \times 10^7 \) m/s. The values of inferred dart-leader speed in Fig. 1d are near the upper end of the range based on optical measurements (the highest measured value is 4.9 \( \times 10^7 \) m/s; Jordan et al. 1992) or in the range of return-stroke speeds (e.g., Rakov et al. 1992). Thus, it appears that our simple model tends to overestimate dart-leader speeds. However, it should be noted that (1) our speed estimates are for the bottom 11 m (\( H = 11 \) m for \( r = 15 \) m) of the channel, (2) optical measurements yield speeds averaged over some hundreds of meters, and (3) there is a tendency for the dart leader to accelerate as it approaches ground (Wang et al. 1999c). It seems to be possible that the speed of the downward dart leader very close to the ground becomes comparable to that of the return stroke, although the higher than expected dart leader speed could be due to the presence of an upward connecting leader (Wang et al. 1999a). The latter explanation implies that our estimated leader speed is actually the effective speed of two leaders propagating toward each other just prior to the initiation of return stroke. If the two leaders propagated at the same speed then our dart-leader speeds would be overestimated by a factor of two, and the mean value would be about 3.3 \( \times 10^7 \) m/s, closer to expected values.

RESIDUAL CHARGE NEAR GROUND

The close triggered-lightning electric fields exhibit characteristic V-shaped waveforms (e.g., Rubinstein et al. 1995; Crawford et al. 2001) with the bottom of the V corresponding to the transition from the dart-leader stage to the return-stroke stage. Typically, the return-stroke field change \( \Delta E_{RS} \) (the trailing edge of the V-shaped pulse) is appreciably smaller than \( \Delta E_L \) (the leading edge of the V-shaped pulse), with the field returning to its background value (flattening) within a few tens of microseconds of the beginning of the return stroke. However, sometimes \( \Delta E_{RS} \) is appreciably smaller than \( \Delta E_L \), as illustrated in Fig. 3. We refer to this difference as the residual electric field, \( R.E. = \Delta E_{L} - \Delta E_{RS} \). The residual electric field decreases on a time scale of the order of tens of milliseconds, suggesting that the return stroke leaves some unneutralized charge near ground and that this charge is neutralized by a slower process, other than the return stroke. Within the same flash, some strokes may exhibit an RE, while others do not. For compiling RE statistics, we measured the RE 20 \( \mu \) s after the beginning of the return stroke (see Fig. 3), when the field is expected to return to its background value, and examined its dependence on return-stroke peak current and on distance. There is a clear tendency for larger strokes to be associated with a larger RE, as illustrated in Fig. 4. The residual field is more pronounced at 15 m that at 30 m, suggesting that the residual charge is located very close to the ground. The mean ratio of RE at 15 m and 30 m is 2.9 in contrast with the ratio of \( \Delta E_L \) at 15 m and 30 m of 1.9. For \( \Delta E_L \), the ratio, close to 2 (in an inverse distance dependence), is consistent with a uniform distribution of charge along the channel (Rubinstein et al. 1995; Crawford et al. 2001). For the RE, the ratio of 2.9 suggests a more or less concentrated residual charge above ground.

We modeled the residual charge by an equivalent point charge located above the ground and used our measurements of RE at 15 and 30 m to estimate the magnitude and height of this equivalent charge as a function of time. The results for one stroke are shown in Figs. 5a and b. As seen in these Figures, over about 25 ms, the magnitude of charge rapidly decreases with time, while the height remains approximately the same. These results are representative of the entire data set, except for the cases when surges (M components) occurred after the return stroke and disturbed the quasi-electrostatic solution for the residual charge. The initial values of charge magnitude are typically 0.5 to 2.0 mC, and the heights are 15 to 30 m. The nature of the residual charge is unknown. It could be associated with small branches formed just prior to or during the attachment process at the descending leader tip. Such branches have been observed in long laboratory spark experiments (e.g., Shcherbakov et al. 2002).

REFERENCES


Fig. 1. Lightning properties inferred from measurements of electric fields at 15 m at the ICLRT in 1999, 2000, and 2001. (a) Leader charge density, (b) return stroke speed, (c) leader potential, and (d) leader speed.

Fig. 2. Lightning properties inferred from measurements of electric fields at 30 m at the ICLRT in 1999, 2000, and 2001. (a) Leader charge density, (b) return stroke speed, and (c) leader potential.


