New Observations and Modeling of Dart Leader Initiation and Development with Broadband Interferometric Mapping and Polarization in 3D (BIMAP-3D)

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Abstract

One of the outstanding questions in lightning research is how dart leaders (also called recoil leaders or K-leaders) initiate and develop during a lightning flash. Dart leaders travel quickly (10^6-10^7 m/s) along previously ionized channels and occur intermittently in the later stage of a flash. We have recently reported some insights into dart leader initiation and development based on our BIMAP-3D observations. In this presentation we will expand on that work by combining observations and modeling to try to understand the observed dart leader behaviors. BIMAP-3D consists of two broadband interferometric mapping and polarization (BIMAP) systems that are separated by 11.5km at Los Alamos National Laboratory. Each station maps the lightning VHF sources in a 2D space, and the combination of the 2-station measurements provides a detailed 3D source map. A fast antenna is also included at each station for electric field change measurements. Our previously reported observations suggest dart leaders commonly exhibit an initial acceleration, followed by a more gradual deceleration to a stop. We also modeled the dart leader electric field change with a simple configuration of two point-charges, finding that the modeled tip charge increased in magnitude during the initial acceleration in some simple cases. We now employ a more sophisticated model to better understand the distribution of charge along the dart leader channel, and the background electric field in which the dart leader develops.

With observed 3D leader development and electric field measurements at two BIMAP stations, we seek to estimate the ambient electric field that drives the leader development.

Introduction

The Broadband Interferometric Mapping And Polarization in 3D (BIMAP-3D) system locates very high frequency (VHF) lightning radio sources in 3D (Shao et al. 2023). The system also includes two fast antennas (FA) which measure the field change at the ground. Figure 1 shows an example of this data for one dart leader.

With observed 3D leader development and electric field measurements at two BIMAP stations, we seek to estimate the ambient electric field that drives the leader development.

Cummer (2020) used the total charge moment change and total extent of fast breakdown to estimate the uniform ambient cloud field during lightning initiation. We are essentially expanding on this concept.

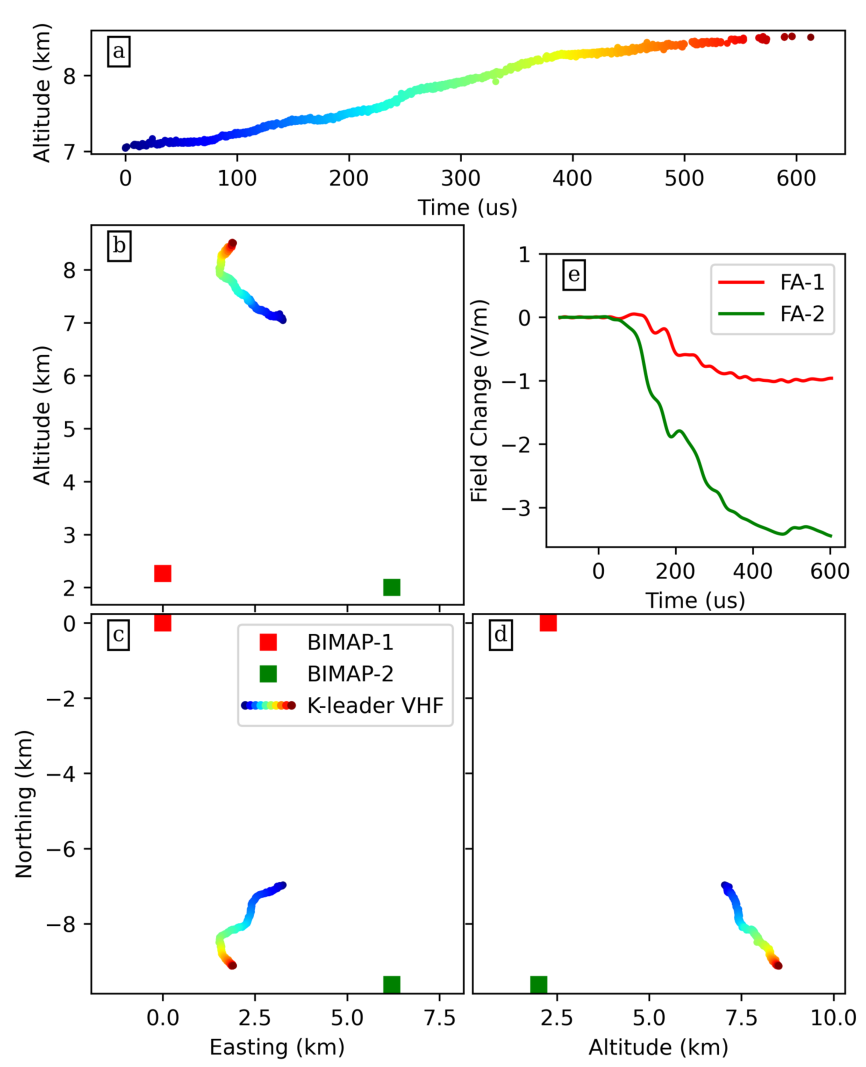

Figure 1. Plot of BIMAP-3D data for one dart leader, showing altitude vs time (a), altitude vs easting (b), northing vs easting (c) and northing vs altitude (d), including the location of the two BIMAP stations. The dart leader sources are colored by time. We also include the field change vs time (e).

We guess an ambient field, use the equipotential leader model to determine the corresponding field change at the ground, then refine our guess to match the measured field change.

Methods

We model the lightning channel as a straight conducting cylinder with a linear charge density,

$$\Phi(s) = \Phi_{amb}(s) + \frac{1}{4\pi\varepsilon_0}\int_{s_a}^{s_b} \frac{\lambda(s')ds'}{\sqrt{(s-s')^2 + r_C^2}}$$

which we can linearize and then invert to solve for a discretized λ

$$[\lambda_j] = [K_{i,j}]^{-1}[\Phi_{amb,i} - \Phi_{cha}]$$

Where Φ_{cha} is the average of the ambient potential along the channel, and $[K_{i,j}]^{-1}$ is a matrix of the capacitance per unit length.

For the charge distribution corresponding to the leader extent at time t_k and any guess at $\Phi_{amb}(s)$ we can then calculate the electrostatic field at the ground as

$$E(X, Y, Z_{grnd}, t_k) = \sum_{i=1}^{N} -\frac{\lambda_i(t_k)\Delta s}{2\pi\varepsilon_0}\frac{z_i - Z_{grnd}}{R^3}$$

We can then compare the modeled field change to the measured field change

$$\chi^2 = \sum_{t_k} \frac{\left(E_{mod}(t_k) - E_{obs}(t_k)\right)^2}{\sigma_k^2}$$

We then iteratively improve our guess of the ambient field using the Levenberg-Marquardt algorithm. We assume the field takes the form of a polynomial of order n to limit the degrees of freedom.

Results

AMBIENT CLOUD ELECTRIC FIELD ESTIMATION

We present electric fields using the atmospheric electricity sign convention, so a positive field will accelerate electrons "forward" in the cloud or "up" from the ground. Figure 2 shows the result of estimating the ambient cloud electric field as a polynomial of degrees between n=0 and n=4. In general, the field is decreasing along the channel for $n > 0$. This is essentially the field distribution we predicted in Jensen et al. (2023) to explain why dart leaders accelerate initially and then slow down to a stop.

The estimated ambient field is low (1-10 kV/m), but this is consistent with previous lightning activity reducing the field along the channel. The tip field starts very low (~150 kV/m), but this could be near the breakdown threshold if the channel is still at ~3000 K from previous activity. The low tip field may also explain why dart leaders appear so narrow in VHF (Hare et al. 2023, Shao et al. 2023), because the field more than a few meters from the tip would be well below the negative streamer stability threshold.

(1) Ambient field decreases along the leader path. (2) Leader tip field is lower than virgin air breakdown threshold. Lower field is due to dart leader retracing previously ionized channel and may explain narrow dart leader VHF path.

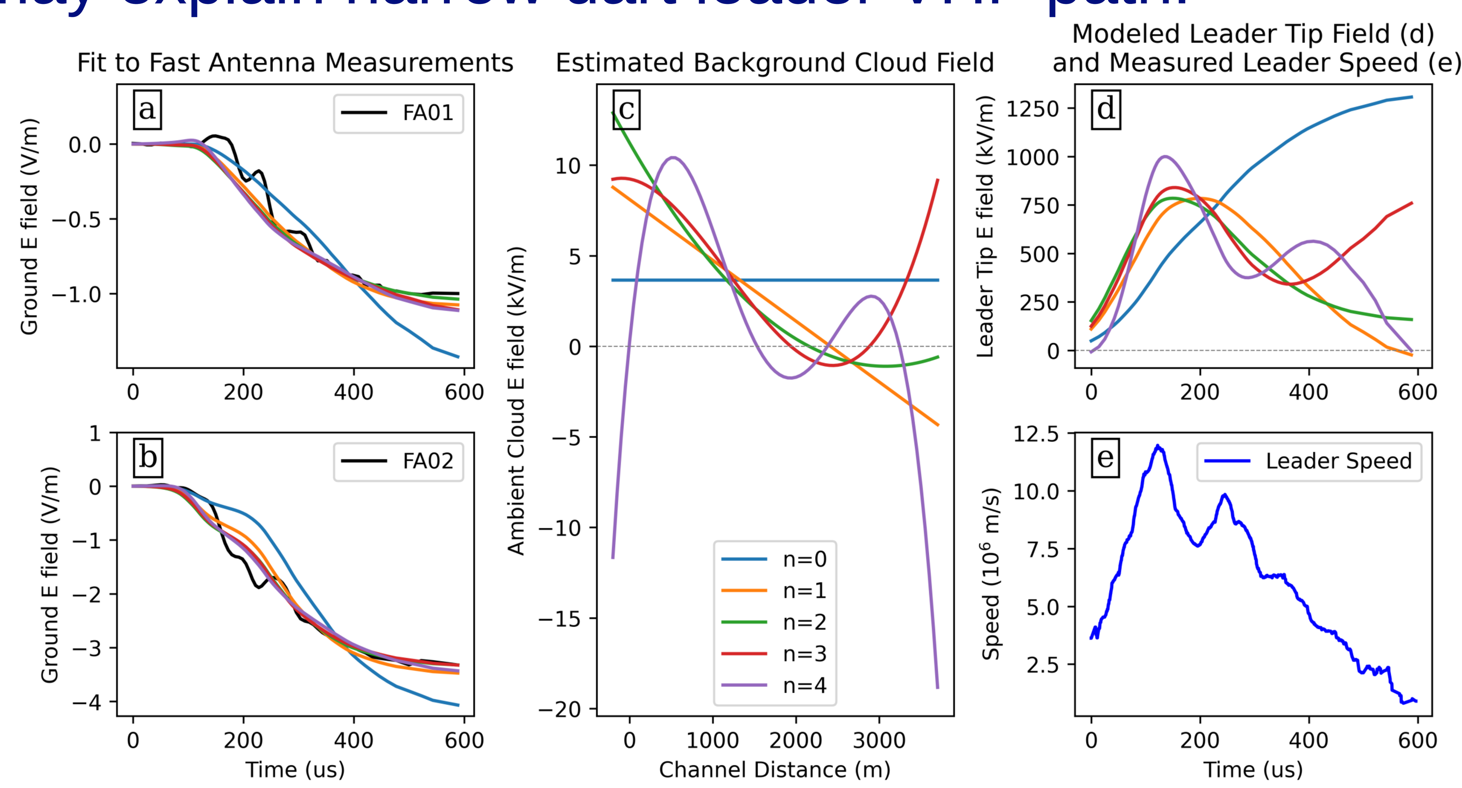

Figure 2. Comparison of the measured and modeled ground electric field vs time for FA01 (a) and FA02 (b), the estimated ambient cloud field vs distance along the channel (c), and the modeled tip field vs time (d). The measured leader speed vs time (e) is included for comparison.

SPEED, TIP FIELD, AND TIP CURRENT

Figure 3 shows a direct comparison of the tip electric field and square root of tip current to the measured leader speed vs time for the n=2 case. The speed and tip field appear to be closely correlated for most of the leader propagation. This matches our guess in Jensen et al. (2023) that variations in leader speed could be explained by variations in the tip field.

The square root of current is also closely correlated with speed. This is not surprising, the tip current is just the speed multiplied by the tip linear charge density, and the charge density is proportional to the tip field. So directly from the model equations we have $I_{tip} \propto v \cdot E_{tip}$. Since we observe $v \propto E$, we must expect $I \propto v^2 \propto E^2$.

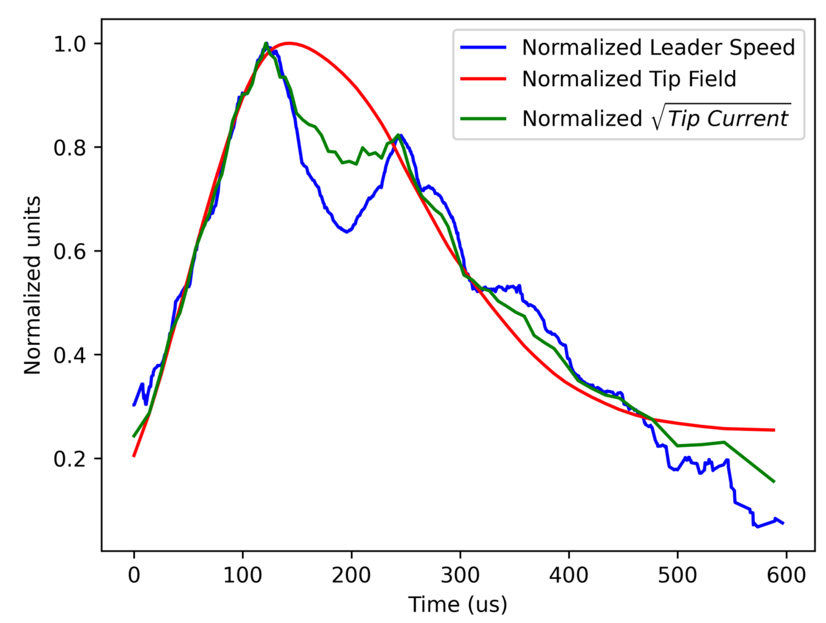

Figure 3. A plot comparing the measured leader speed, modeled tip field, and square root of the modeled current, all plotted against time. Each variable on the y-axis is normalized so that its maximum value is 1.

Leader speed is well correlated with tip electric field and the square root of tip current.

OTHER EQUIPOTENTIAL MODEL RESULTS

Figure 4 shows the potential distribution, linear charge density, and current distribution along the channel for the n=2 case. Each curve is a snapshot of the entire channel at a particular time, and the location of the negative dart leader tip can be tracked as a sharp upward jump in each plot at the transition between the active leader and the inactive channel.

The charge density at the tip increases initially, but then the tip charge density decreases while leaving a significant amount of negative charge along the middle of the channel. The magnitude of the charge density is 10-100x smaller than typical estimates of around 1 C/km, but this is consistent with a channel field 10-100x smaller than the ~100 kV/m E-field a stepped leader in virgin air would propagate through. The modeled current for this dart leader has a peak value of about -500 A, which seems reasonable.

The analysis also gives time-dependent (1) leader potential, (2) charge density, and (3) current along the channel.

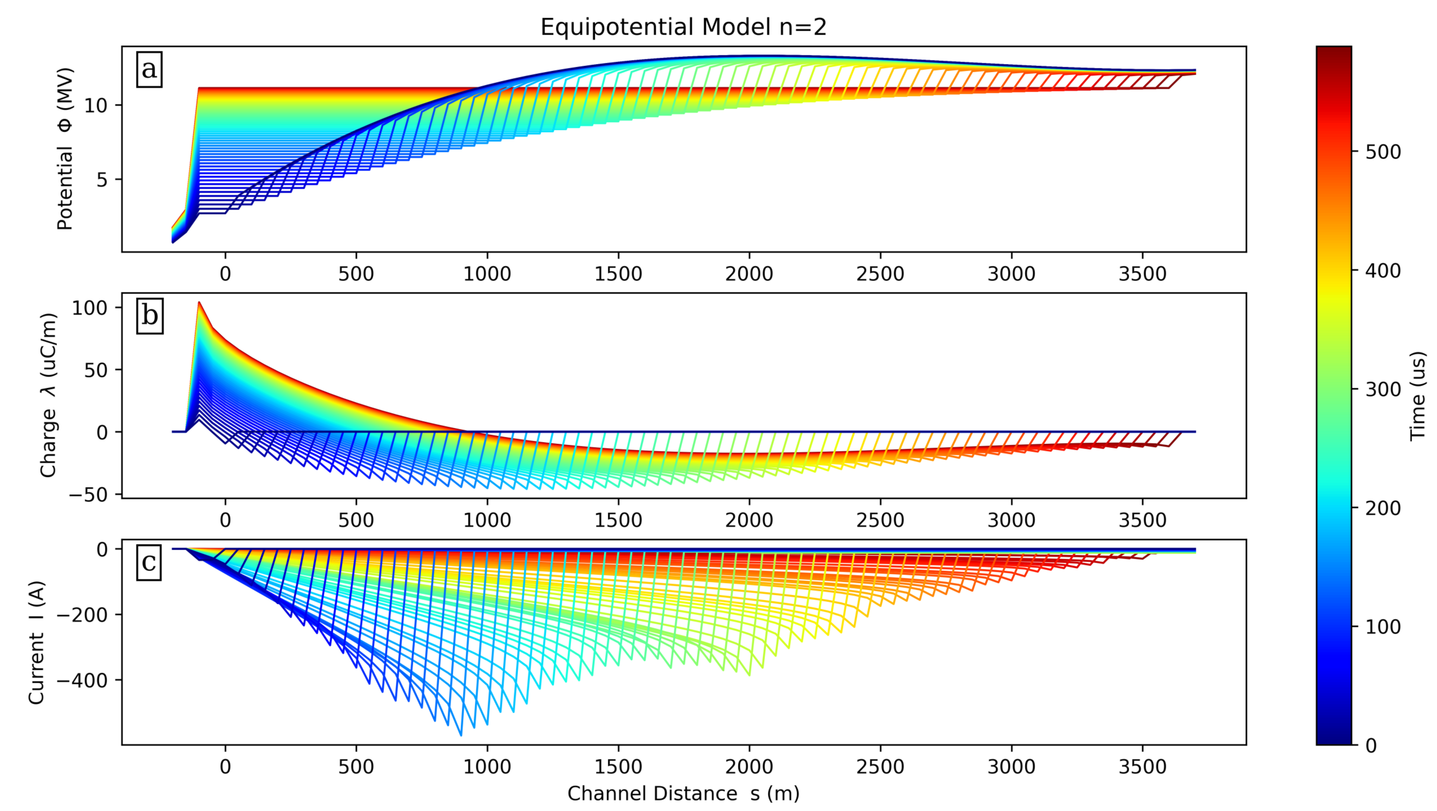

Figure 4. Plots showing the potential (a), linear charge density (b), and current (c), all plotted against distance along the channel. Each curve shows a snapshot of the channel at a time indicated by the color.

Conclusions

1. The ambient electric field along a lightning channel can be estimated using 3D mapping data along with calibrated electric field change measurements.
2. Electric fields along channels with previous leader/return-stroke activity may be significantly reduced compared to typical ~100 kV/m cloud fields.
3. As predicted by Jensen et al. (2023), the ambient field along the channel starts relatively high and then decreases, leading to a tip field that first increases then decreases, explaining dart leader acceleration and deceleration.
4. Low tip fields are consistent with a ~3000 K pre-dart-leader channel and may also explain why dart leaders are so thin in VHF.
5. Dart leader speed is correlated with leader tip electric field, and with the square root of tip current.
6. Once the ambient field is estimated the equipotential model also provides us with the channel potential, charge density, and current distribution along the channel resolved in space and time.

Citations:

Cummer, S. A. (2020). Indirectly measured ambient electric fields for lightning initiation in fast breakdown regions. *Geophysical Research Letters*, 47 (4), e2019GL086089. https://doi.org/10.1029/2019GL086

Hare, B. M., Scholten, O., Buitink, S., Dwyer, J. R., Liu, N., Sterpka, C., & ter Veen, S. (2023). Characteristics of recoil leaders as observed by lofar. *Phys. Rev. D*, 107 , 023025. https://link.aps.org/doi/10.1103/PhysRevD.107.023025

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