Determination of Charge Movement in Intracloud Lightning Flashes

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ABSTRACT:
The goal of this study is to analyze and characterize the charge movement and neutralization in intracloud (IC) lightning. To accomplish this, we incorporate electric field change measurements and source locations from the Huntsville Alabama Marx Meter Array (HAMMA) and source locations from the North Alabama Lightning Mapping Array (NALMA) into our analyses. The HAMMA source locations are determined by applying TOA techniques to the peaks of the bipolar pulses commonly seen in IC electric field waveforms. Using these locations along with those determined by the NALMA as the positions from which charge is being moved, we then model the electrostatic field output at up to 7 HAMMA sensors. Our model uses Markov Chain Monte Carlo (MCMC) techniques to determine the best-fit values of the position to which charge is moved in addition to the amount of charged being moved. Charge may be transferred between the positive and negative regions (i.e. neutralized) or simply rearranged within either region; both cases are accounted for by our model. The results of this analysis for 2 or more IC flashes that occurred on 25 October 2010 will be presented.

INTRODUCTION

A lightning discharge moves electric charge from one location to another, which is manifested by, among other things, a change in the measured electric field. This fact has been used to investigate charge transfer in both cloud-to-ground (CG) lightning [e.g., *Krehbiel et al.*, 1979] and intracloud (IC) lightning [e.g., *Hager et al.*, 2010; *Lu et al.*, 2011]. In this study, we use the Huntsville Alabama Marx Meter Array (HAMMA) and the North Alabama Lightning Mapping Array (NALMA) to investigate the charge structure of IC lightning. Using HAMMA and NALMA data collected on 25 October 2010 we apply the dipole model of IC discharges, through Markov Chain Monte Carlo (MCMC) techniques, to determine the magnitude and location of the neutralized charge. To be considered for analysis an IC flash must meet the following criteria: (1) it must occur near the sensor network, (2) it must be sufficiently isolated in space and time such that the electrostatic waveform was not contaminated by field changes from any other flashes, and (3) at least 6 HAMMA sensors recorded the entire flash. Here, we briefly describe the instrumentation utilized in our analysis, our methods for determining the magnitude and position of the neutralized charge, and present a sample data set along with example fits from our model to the HAMMA waveforms.

INSTRUMENTATION

The North Alabama Lightning Mapping Array (NALMA) [*Goodman et al.*, 2005] is a network of sensors designed to detect VHF radiation from lightning-related discharges. This network detects pulses in the 76-82 MHz range and uses time-of-arrival to find source locations.

The Huntsville Alabama Marx Meter Array (HAMMA) [*Bitzer et al.*, 2013] is a network of seven electric field change meters in Huntsville, Alabama and the surrounding area. The sensors detect in the VLF regime and have a decay time constant of $100\,\mathrm{ms}$. The sampling rate for the HAMMA sensors is $1\,\mathrm{MS/s}$. Typical baselines for HAMMA are $\sim$10-15 km, and the array lies within the NALMA domain.

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METHODS

We use the standard dipole model to determine the location and magnitude of the rearranged charge in an IC flash. That is, based on conservation of charge, we assume that equal and opposite charges are neutralized by the discharge. The dipole field change is given by

$$\Delta E = \frac{Q}{2\pi\epsilon_0}\left[\frac{z_p}{[(x_i-x_p)^2+(y_i-y_p)^2+z_p^2]^{\frac{3}{2}}}-\frac{z_n}{[(x_i-x_n)^2+(y_i-y_n)^2+z_n^2]^{\frac{3}{2}}}\right], \tag{1}$$

where Q is the charge magnitude; x_i and y_i are the sensor locations ($z_i = 0$); x_p, y_p, and z_p give the location of the positive charge; and x_n, y_n, and z_n give the location of the negative charge.

There are seven unknowns (i.e. model parameters) in equation 1; hence, we need at least seven measurements to solve for the parameters based solely on field changes. Practically, however, it is difficult to determine good solutions without having at least one more measurement than parameters. This limitation can be overcome by using other data sets to determine a subset of the parameters. For example, HAMMA and NALMA time-of-arrival locations can be used to constrain the position of one end of the dipole, thus reducing the number of unknown parameters from seven to four.

We apply Markov Chain Monte Carlo (MCMC) techniques [e.g. *Gilks et al.*, 1995] to solve for the unknown parameters. Essentially, what this does is step through a "chain" where at each link a new set of parameter values is drawn from a proposal distribution and is then accepted or rejected based upon a comparison of the likelihoods of the proposed solution and the previous accepted solution. In this way, the Markov Chain converges to a set of best-fit values for the unknown parameters.

DISCUSSION and CONCLUSION

Shown in Figure 1 is the HAMMA/NALMA data from an IC flash on 25 October 2010. The ladder plots on the left-hand side show the HAMMA waveforms and the time-of-arrival source altitudes with time, and the right hand side show the spatial distribution of the time-of-arrival sources. We then apply the methods discussed above to determine the model parameters. An example of the resulting electric field model-fits are shown in Figure 3 for two of the HAMMA sensors (HAMMA 5 and HAMMA 7). Upon examination of Figure 3, it is apparent that after $\sim$150 ms the model-fit in the upper plot diverges from the data. This could be indicative of charge movement not readily detected by all HAMMA sensors due to geometrical factors.

For example, shown in Figure 2 is the distribution of charge magnitudes (i.e. the dipole charge neutralized by each source) based upon preliminary results corresponding to the flash shown in Figure 1. For the results shown the mean charge magnitude is 13 mC, and the median is 8 mC. Occasionally, there is some ambiguity in the output; for instance, a large charge magnitude may be associated with a very narrow dipole spacing, which is likely not a true result. As we continue with the error analysis and characterization of the results these ambiguous cases are being reanalyzed to resolve this.

The complementary use of HAMMA and NALMA provides a quality data set for investigating the charge structure of IC lightning. In this continuing analysis we are examining the magnitude and location of the neutralized charge with the goal of understanding the electrical energy release of intracloud lightning.

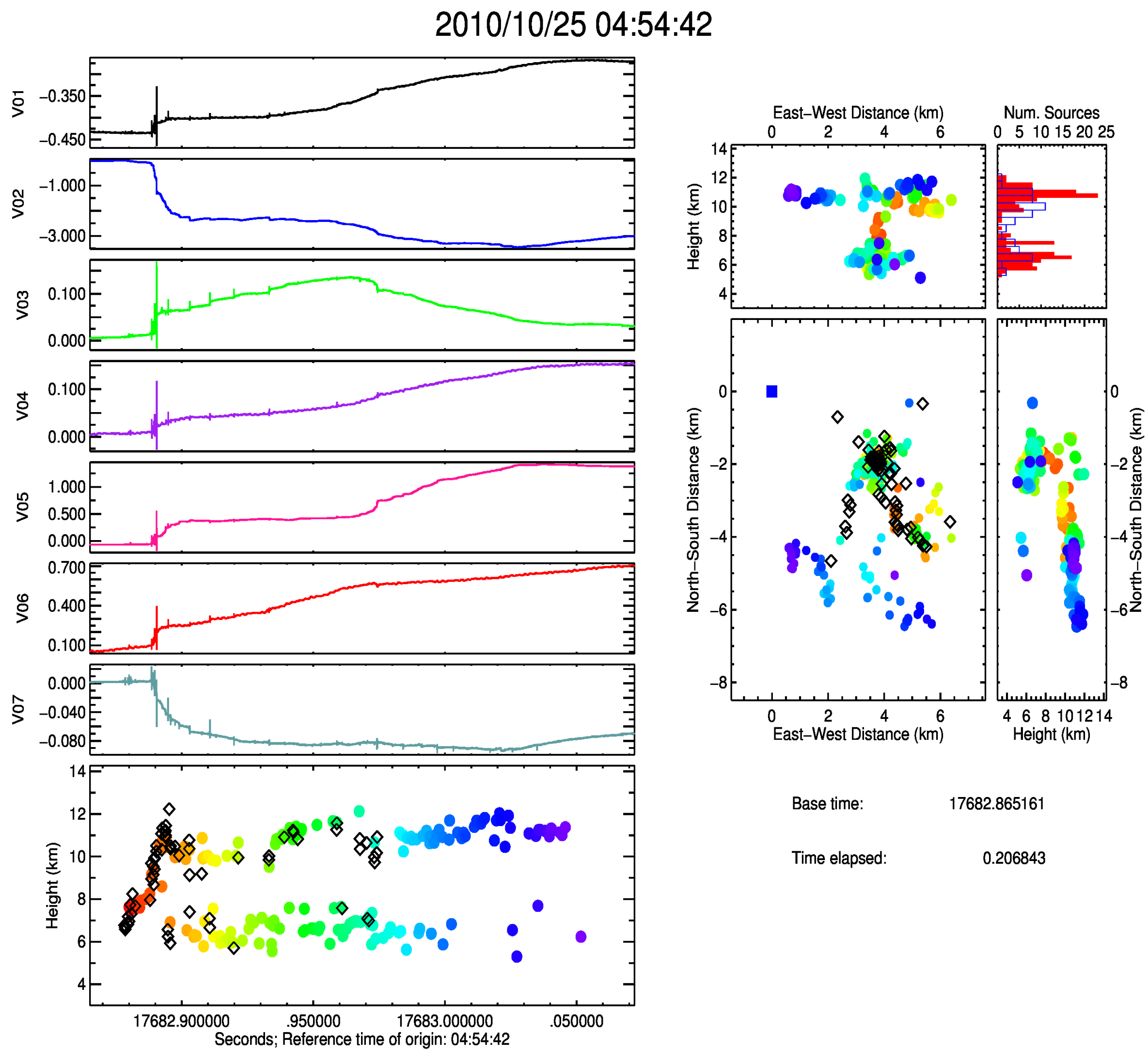

Figure 1: An example data set consisting of (1) HAMMA waveforms (V01-V07), (2) HAMMA time-of-arrival sources (black diamonds), and (3) NALMA data (colored circles). The blue square in the plan view NALMA plot represents the HAMMA 2 sensor.

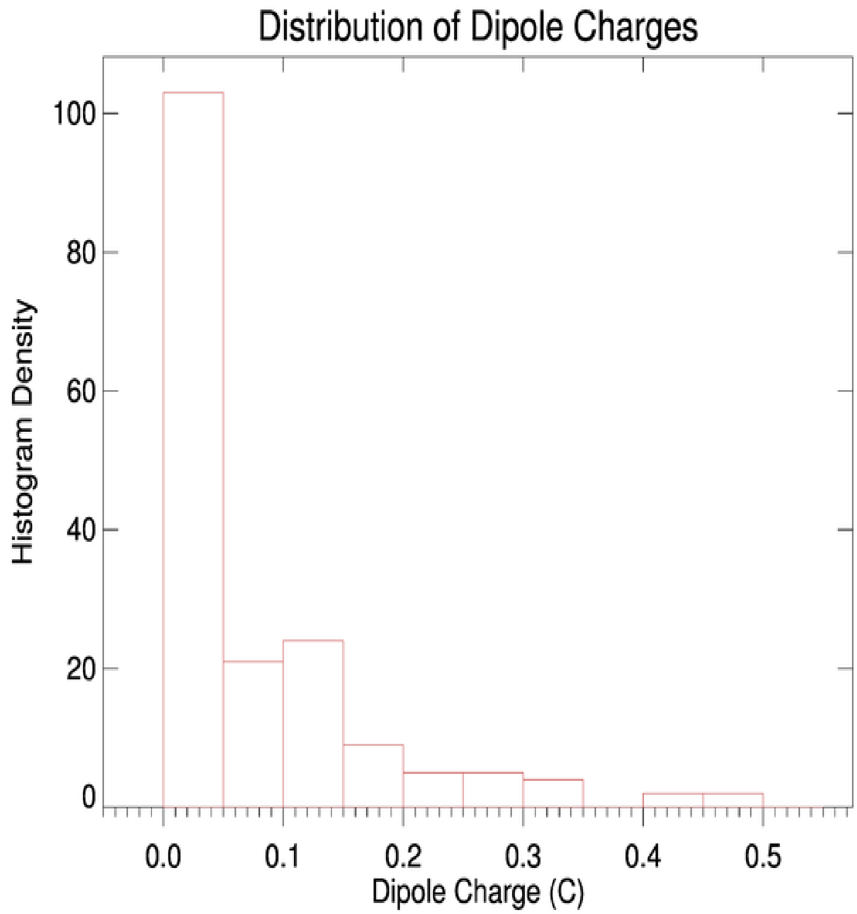

Figure 2: The distribution of model-derived charge magnitudes for the dipole charges.

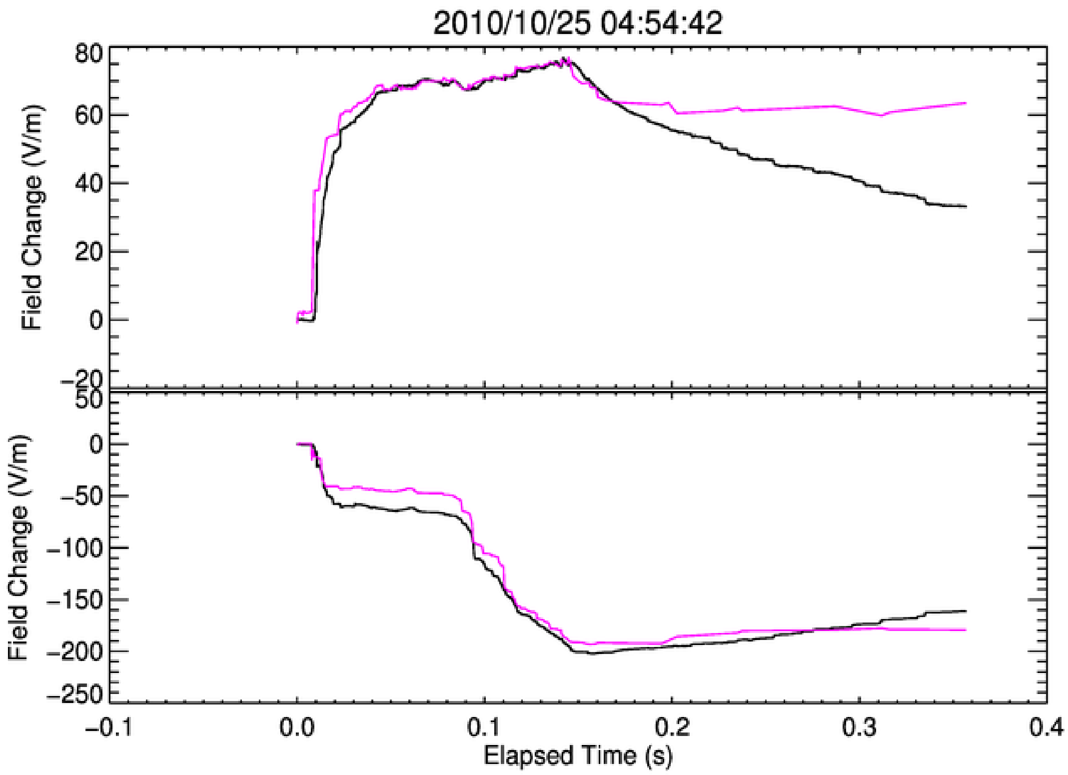

Figure 3: An example fit to two of the HAMMA waveforms. The black lines represent smoothed HAMMA data and the magenta lines represent the model-derived data.

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