Development of Novel Data Analysis Techniques for Multi-Point Mapping of Thunderstorm Electrical Structures

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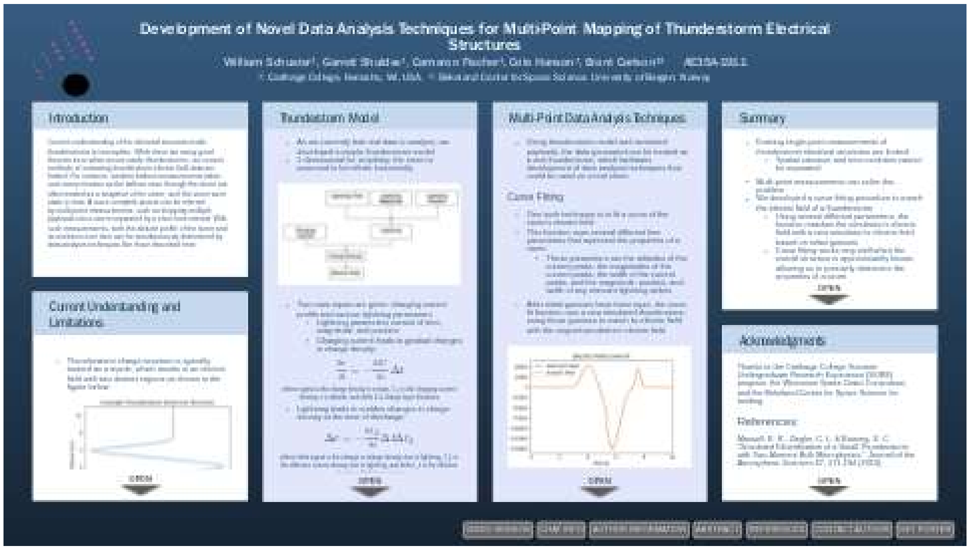
Abstract

Current thunderstorm electric field data analysis methods provide only an incomplete understanding of thunderstorm structure and evolution, since these methods typically rely on data from a single weather balloon payload. The electric field measured by a single payload is dependent on both height and time, and it is not possible to separate the two. However, this limitation can be overcome if multiple payloads are used, enabling novel data analysis. First, considering a given time, measurements made by multiple instruments at different altitudes provide a view of the altitude profile of the electric field and how that profile evolves with time. Second, considering a given altitude, measurements made by multiple instruments as they pass that altitude at different times provide an estimate of the average current flowing past that altitude and how that current varies with height, though correction for field changes due to lightning is necessary. Third, such observations can be used as the target for simulated storm behavior in a fitting process to simultaneously determine properties of the charging current, storm geometry, and lightning properties. Tests of these techniques on simple simulations of thunderstorms and lightning show promise and suggest a useful path forward for multi-point measurement of thunderstorm electrical structures.

Development of Novel Data Analysis Techniques for Multi-Point Mapping of Thunderstorm Electrical Structures



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PRESENTED AT:

INTRODUCTION

Current understanding of the electrical structure inside thunderstorms is incomplete. While there are many good theories as to what occurs inside thunderstorms, our current methods of extracting thunderstorm electric field data are limited. For instance, weather balloon measurements taken over many minutes as the balloon rises through the storm are often treated as a snapshot of the storm, as if the storm were static in time. A more complete picture can be inferred by multi-point measurements, such as dropping multiple payloads into a storm separated by a short time interval. With such measurements, both the altitude profile of the storm and its evolution over time can be simultaneously determined by data analysis techniques like those described here.

CURRENT UNDERSTANDING AND LIMITATIONS

- Thunderstorm charge structure is typically treated as a tripole, which results in an electric field with two distinct regions as shown in the figure below
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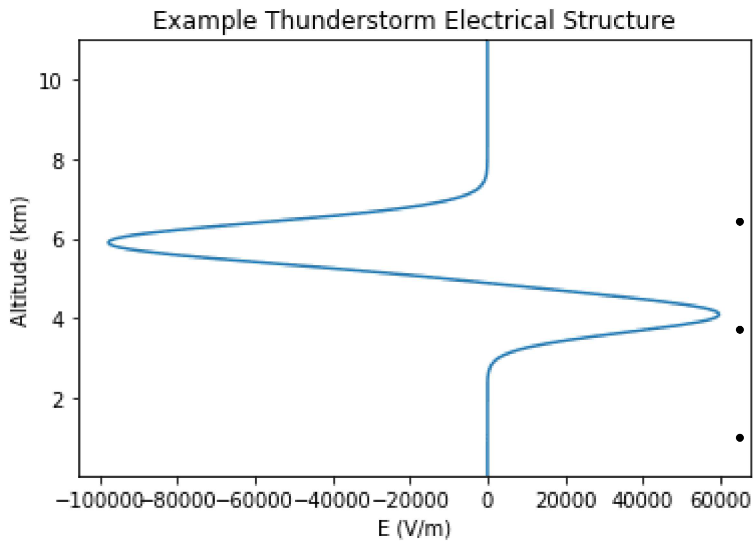
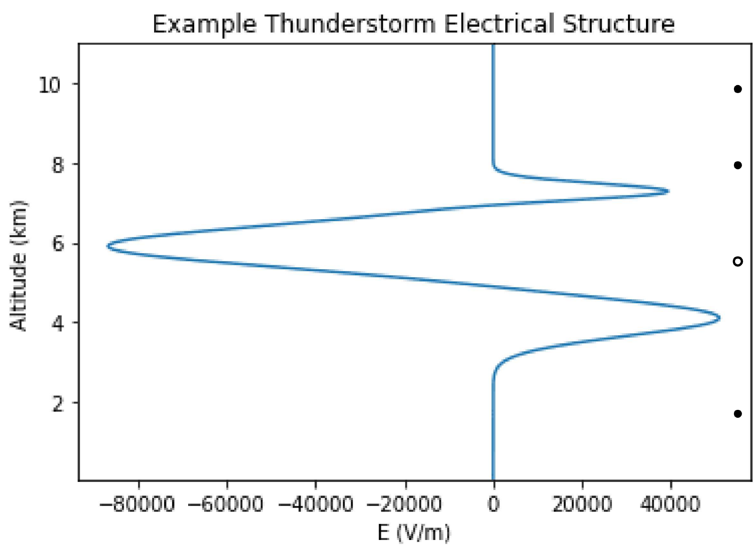


Oftentimes, thunderstorms have a slight negative screening layer on the top, resulting in an electric field with three regions, as discussed in Stolzenburg and Marshall (2008), and as shown in the figure below

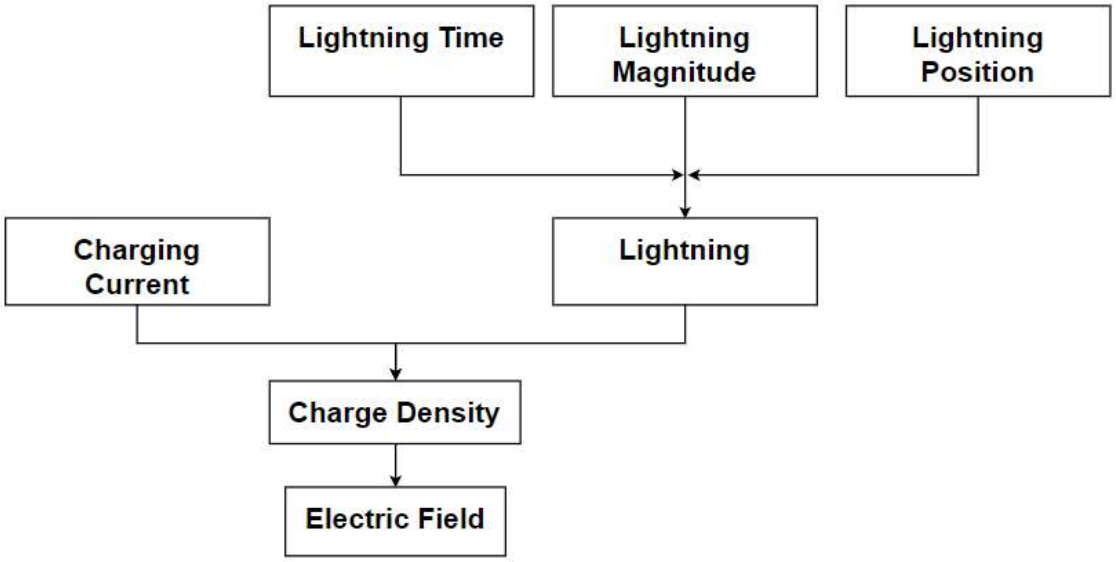


- Current structure is derived from balloon measurements of electric fields inside storms
- Derivation assumes that storms don't significantly evolve as a balloon goes through it
- Current and lightning move charges over much shorter timescales, so these measurements ignore important electrical evolution over short time intervals
- Multi-point measurements provide path forward
- Previous studies, i.e. Stolzenburg and Marshall (2008), have utilized multi-point measurements
  - These measurements have very large time separations, providing valuable information about overall evolution
- Short-interval studies can fully map structure at any one time or map short-duration evolution

We are preparing to carry out such short-interval experiments by methods further discussed in Fischer et al., poster AE35A-1912 in this session. This poster, on the other hand, describes how such data might be analyzed in order to separate spatial structure and time evolution by using a simple thunderstorm model and analyzing it to compare inferred characteristics with the known input of the model.

THUNDERSTORM MODEL

- As we currently lack real data to analyze, we developed a simple thunderstorm model
- 1 dimensional for simplicity; the storm is assumed to be infinite horizontally



- Two main inputs are given: charging current profile and various lightning parameters
  - Lightning parameters consist of time, magnitude, and position
  - Charging current leads to gradual changes in charge density:

$$\frac{\partial \sigma}{\partial t} = -\frac{\partial J_C}{\partial z}\Delta z$$

where sigma is the charge density in a layer, J_c is the charging current density, z is altitude, and delta Z is charge layer thickness

- Lightning leads to sudden changes in charge density at the time of discharge:

$$\Delta \sigma = -\frac{\partial J_L}{\partial z}\Delta z \Delta t_L$$

where delta sigma is the change in charge density due to lightning, J_L is the effective current density due to lightning, and delta t_L is the effective duration of lightning current

- Charging current is assumed to be constant throughout storm's lifetime
- Charging and lightning current profiles constructed using Gaussian distributions
- An initial delay is given to the model so a charge density can form before data is collected
- Electric field is then calculated using charge density
- After the electric field throughout the storm at one time is calculated, the model begins calculating it at the next time
- Simulated payloads rise through the storm, recording electric field at its current height

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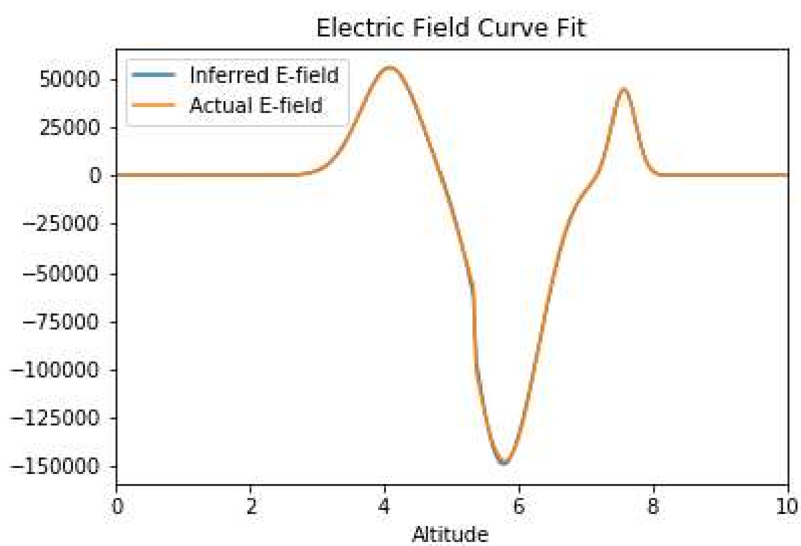
This is a very simple model of a thunderstorm. While more sophisticated models exist, such as Mansell, Ziegler, and Bruning (2010)'s thunderstorm model and Riousset et al. (2007)'s lightning model, this model still provides useful data.

MULTI-POINT DATA ANALYSIS TECHNIQUES

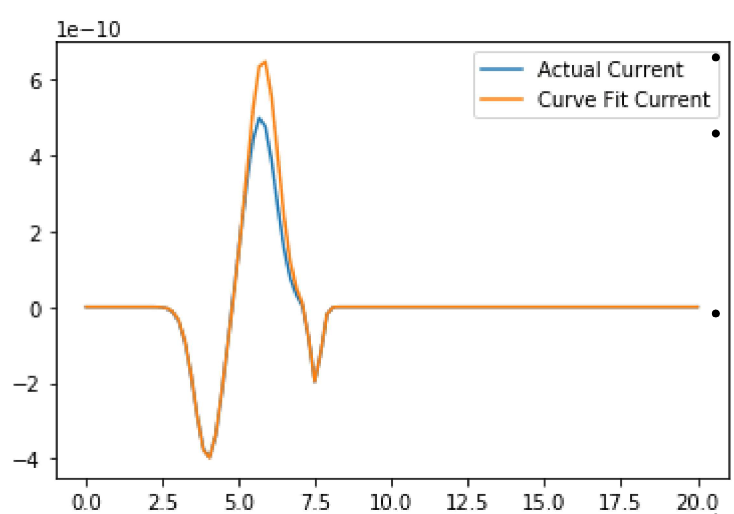
- Using thunderstorm model and simulated payloads, the data generated can be treated as a real thunderstorm, which facilitates development of data analysis techniques that could be used on a real storm

Curve Fitting

- One such technique is to fit a curve of the storm's electric field
- This function uses several different free parameters that represent the properties of a storm
  - These parameters are the altitudes of the current peaks, the magnitudes of the current peaks, the width of the current peaks, and the magnitude, position, and width of any relevant lightning strikes
- After initial guesses have been input, the curve fit function runs a new simulated thunderstorm using those guesses to match its electric field with the original simulation's electric field



- Generally, the curve fit matches the electric field very well
- However, with so many free parameters, the curve fit becomes very complex



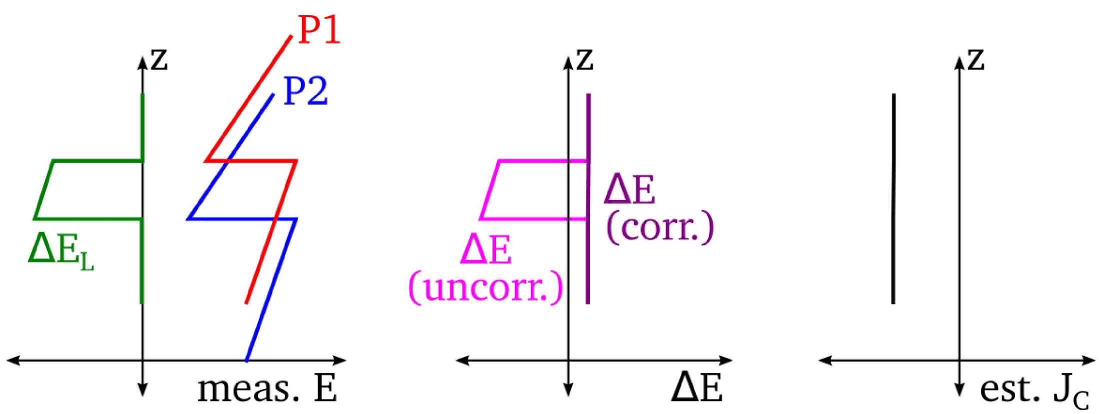
- Curve fitting is only as good as initial guesses
- Curve fit is sometimes poorly constrained, due to number of free parameters

Direct Calculation of Current

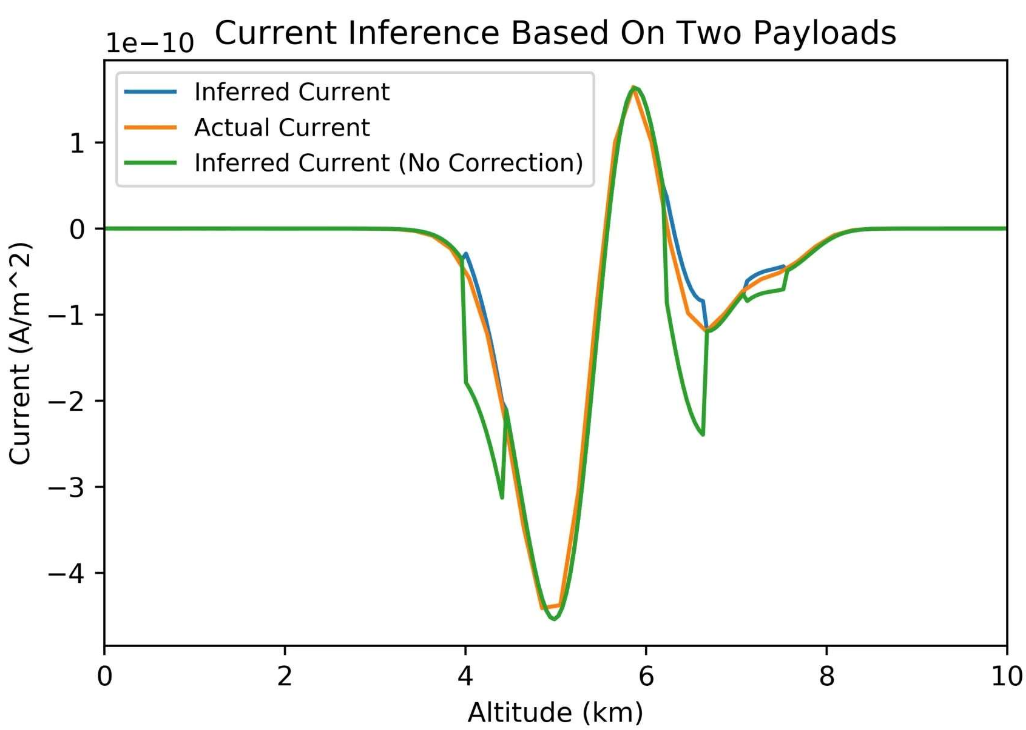
- Another technique is to calculate the current density at every altitude in the storm by using the change in electric field of the storm as measured by two payloads separated by a short (~1 minute) time interval
- Both payloads, separated by a short time interval, record electric field at every altitude
- Using both payloads' measured electric fields at a certain altitude, and the time each payload reached that altitude, the current density is calculated using the change in electric field divided by the time interval

$J_c = \epsilon_0 (E_2 - E_1)/\Delta t$

- However, this assumes the field change is solely due to charging current
  - If lightning contributes to overall current, corrections must be applied
  - These corrections can be determined by interpolation of lightning-induced field changes measured by each payload at the altitude of interest



- While the interpolation is linear, it still performs very well



- The current inference function has some limitations, however
  - To negate lightning E-field changes, the payloads need to be closely spaced in time
  - To measure slow charging processes, both payloads need to be spaced far apart in time

    - The interpolation function assumes linearity, which can result in the function overcorrecting the change in electric field

- Despite the limitations, these two techniques have shown promise and could be a useful path forward in our understanding of thunderstorms

SUMMARY

- Existing single-point measurements of thunderstorm electrical structures are limited
  - Spatial structure and time evolution cannot be separated
- Multi-point measurements can solve this problem
- We developed a curve fitting procedure to match the electric field of a thunderstorm
  - Using several different parameters, the function matches the simulation's electric field with a new simulation's electric field based on initial guesses
  - Curve fitting works very well when the overall structure is approximately known, allowing us to precisely determine the properties of a storm
  - The curve fit requires accurate initial guesses due it being poorly constrained
- We developed a method to calculate the current of a thunderstorm at every altitude
  - Using electric field measurements from two payloads, a change in electric field can be calculated, which in turn can be used to calculate a current
  - This function requires no assumptions, and works very well when the appropriate data (i.e. lightning strike times) exists
  - The function can sometimes overcompensate for lightning, partially due to the linear nature of the interpolation

Future Work

- Refine fit functions to reduce variability in free parameters
- Use curve fit lightning profiles to improve current interpolation function

ACKNOWLEDGMENTS

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Mansell, E. R., Ziegler, C. L. & Bruning, E. C. "Simulated Electrification of a Small Thunderstorm with Two-Moment Bulk Microphysics." *Journal of the Atmospheric Sciences* 67, 171-194 (2010).

Riousset, Jeremy A., Victor P. Pasko, Paul R. Krehbiel, Ronald J. Thomas, and William Rison. "Three-Dimensional Fractal Modeling of Intracloud Lightning Discharge in a New Mexico Thunderstorm and Comparison with Lightning Mapping Observations." *Journal of Geophysical Research* 112, no. D15 (2007).

Stolzenburg, Maribeth, and Thomas C. Marshall. "Charge Structure and Dynamics in Thunderstorms." *Space Science Reviews 137,* no 1-4 (2008).

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