Integrated methods for understanding charge transport and distribution inside active electrical storms

ABSTRACT / SUMMARY OF PROPOSED WORK

A “lightning mapping array” (LMA) yields detailed spatio-temporal maps of lightning discharges by locating emitted radio-frequency (RF) radiation associated with channel breakdowns. Because the LMA is has 10-100 microsec. resolution, it increases the importance to develop new techniques that measure charge transport on the same time-scale. The innovation I propose is an airborne time-resolved “field-change” sonde (TRFCS) to study charge transport. Initially balloon-launched, the device is to be refined until it is small enough to be dropped from an aircraft.

Ground-based TRFCS’s have been used, though the presence of the Earth’s ground-plane causes only the vertical component of E to give useful information. Further, ground-based sensors are usually far from the lightning channels so that data-interpretation is complicated. DC-field sondes (DCS) have been used in balloon soundings to learn most of what is known today about the parent cloud charge structure. The frequency response of a DCS is typically 0-10 Hz. My proposed TRFCS (frequency response 10 Hz-100 kHz) will be used in the following scientific studies:

1) One TRFCS enables quantification of the charges transported along a nearby lightning channel whose position is determined by an LMA. It also allows measurement of charges transported along the channel after it is well-ionized and no longer emitting the RF that makes it visible to the LMA.

2) Multiple TRFCS’s enable a resolution of the difference between time-variation and space variations of charge, and a 3-D mapping of parent charges. Thunderstorm data to date is mostly 1-D (charge vs. altitude), though recent work is extending it to 3-D. I would add the time-resolved element to these studies.
A) Lightning – Exciting, Dangerous!
Somewhere on Earth lightning strikes roughly every second of the day. A lightning stroke is dramatic (−40 kAmp, 100 MVolt, 30,000 K), and in the last decade, we have begun to finally understand it. Lightning protection is a social benefit, and short-term lightning prediction is now practiced. (DC electric "field-mills [Winn78] deployed outdoors provide several minutes warning because the vertical component of the E-field increases from its fair-weather value of roughly -100 V/m to +10 kV/m in the 10 minutes in which an electrical storm-cell develops.)

B) State of Art – Lightning energetics, the LMA and “The Potential Well Model”
The state of understanding in this area can be found in recent papers such as Coleman et al. [Coleman02]. (Figures 1 and 2 are taken from that publication.) Data is interpreted via a simple model of lightning energetics. A lighting flash gets its energy from the electrostatic energy density \( \frac{1}{2} \rho V \) (with \( \rho \) = local charge density and \( V \) the local potential). Given that clouds may be modeled as electric tripoles [Williams89], it is most energetically favorable for the flash to deposit positive charge in a predominantly negative charge-center, or vice-versa [Proctor91]. Figure 2 shows experimentally measured potential through a storm, obtained by integrating E-field from a balloon-launched DCS along the z-axis. Experiments confirmed that positive flashes deposited their charge in the negative potential well around 7 km. Likewise, negative flashes deposited their charge in the positive well around 9 km. Figure 1 hints at the power of the LMA. [Rison99 for full details]. A representative flash is plotted as altitude vs. time by location of its RF emissions. Note that most of the data points of the negatively discharge are concentrated at 9-10 km (near the + potential well). A positively charged branch is concentrated around 7 km (near the - potential well). In particular, data verifies predictions that flashes should arise in the highest-field regions of the cloud, and deposit charge, for intercloud (IC) flashes, in “potential wells” appropriate to the sign of the charge.
Also apparent from Fig. 1 is the relative paucity of data points corresponding to the positive discharge. This is a known lightning-RF phenomenon and allows one to distinguish negative from positive discharges.

C) The Problems
I want to address two problems; quantifying the transport of charge by a lightning flash, and the related (more-studied) problem of the parent distribution of charge in a thunderstorm. Field change data (\( \Delta E \)) addresses the first problem, while the DC-field data (simply “E”) addresses the second. I want to take the data interpretation of the parent distribution beyond the tripole model and address horizontally varying as well as vertically varying charge distributions. I hope from the \( \Delta E \) data to get a more detailed view of the local charge “pockets” created by IC flashes. Progress will be enabled by a new generation of instrument to be developed and by correlation with LMA data. This research can lead to stronger confirmation of the potential-well model. Not all experimental data fits this model. The deviations are currently explained as being caused by horizontal and temporal variations in charge. Characterizing these with new-generation instruments will either confirm the model or suggest ways in which it must be modified.

D) Broader Scope
Previous-generation electrical sondes (DCS) [Winn75] have been in productive use for nearly 30 years by the electrical-storm community. This encourages one about potential contributions of new instruments. Generally, electrical characterization opens a window into the heart of many significant activities in electrified storms.

E) Plan of Procedure
Recent developments enable pursuit of the detailed distribution of charges and the effect of charge locations on the path of the lightning stroke, which improves understanding of the entire discharge process. To that end, I propose to develop a next generation of electrical sonde integrating telemetry and global-positioning system (GPS) with 100-kHz vector field change (\( \Delta E \)) and vector DC E-field meters. I call the whole instrument a TRFCS (Time-resolved field-change sonde) as that captures its most novel features. However, several other features are novel. The TRFCS will be
physically compact. It will be based around a modern computing platform (an embedded Linux Pentium PC-104+ computer board with integrated data acquisition). It will use packet-radio or spread-spectrum communications for telemetry. It will have substantial local storage in flash memory so that additional data can be recovered if the instrument survives its landing. It will of course integrate pressure, temperature, and humidity sensors to its electrical measurements.

This TRFCS will let us attack the problem of charge transport in greater detail than has previously been achieved. Our methodology overcomes two problems:

1) **The inversion problem.** The inversion problem, simply stated, is that a space-charge distribution produces a uniquely determined E-field, but a given set of E-field measurements can be produced by an infinite number of space-charge distributions. Until now, DC E-field measurements (not time-resolved ΔE measurements) were analyzed to yield static charge distributions (but not transport), because there existed charge models to which data could be fit. [These models are the tripole model, and more generally the 1-D model that \( \rho(z) = \varepsilon (\Delta E_z / \Delta z) \).] Now, with the advent of the LMA, we have additional information. If one uses LMA data to indicate the position of the lightning channel, then one can interpret ΔE data to find the overall charge transferred and its distribution along the one-dimensional (though highly ramified) channel. While there is still an inversion problem, the range of possible charge distributions is greatly constrained by the independent knowledge of the channel. It should be straightforward to distinguish between a model in which the bulk of the charge transported is concentrated at the growing tip of the stroke and in which a constant linear density is left behind. (See figure 5). Other exciting things we can hope to learn include how the charge is divided up when the lightning channel reaches a branch point.

2) **The difficulty of multiple simultaneous measurements.** Stolzenberg, Marshall and Rust, who launched several DCS’s simultaneously [Stolzenberg01], give the state of the art in this respect. With their several grad. student team, they launched several balloons with sondes over a 30-minute period. It is unlikely that one can do much better than this with balloons, so our ultimate goal is a payload small enough that it can be launched from an aircraft dropsonde tube. Research aircraft, like the future NCAR Gulfstream-V, are now capable of getting above all significant storms and dropping instruments in any desired pattern or density. This multi-launch capability will benefit both the study of DC-fields (E) and charges and the study of charge-transport via ΔE.

**Instrumentation:**

Functionally, a field-change meter is similar to instruments that measure the DC component of E, except the field-change meter does not periodically shield its sensor to determine the output voltage that corresponds to E=0. The field-change meter of Fig. 3 would be sensitive to frequencies between 10 Hz and 100 kHz. There would be eight electrodes, four of which would be used for sensing ΔE. The positions of three of them, numbered 1, 3, and 6 are visible in the figure; number 8 is behind the cylinder, opposite number 6. The other four “dotted” electrodes would be used to measure the three DC-components of the electric vector \( \vec{E} \). These (2, 4, 5, and 7) would be recessed in openings in the outer cylindrical housing, and a rotating cylindrical shutter inside the outer cylinder would periodically cover the electrodes. Subtractions similar to those for ΔE described above will give the three components of \( \vec{E} \). This method of measuring \( \vec{E} \) is the same as that used previously on rockets [Marshall95]. The electrodes would be insulated from the conducting surface of the cylinder and connected to amplifiers inside the cylinder to sense the variations in the induced charges \( \Delta Q_i (i = 1..8) \). One horizontal component (ΔE\( _x \)) would be approximately proportional to the difference in the induced charges on electrodes 1 and 3 (\( \Delta E_x \sim \Delta Q_1 - \Delta Q_3 \)). Similarly \( \Delta E_y \sim \Delta Q_6 - \Delta Q_8 \). Finally, \( \Delta E_z \sim (\Delta Q_1 + \Delta Q_3) - (\Delta Q_6 + \Delta Q_8) \).
Figure 4 shows four items. In the foreground is the internals of a state of the art pressure, temperature and humidity dropsonde with GPS and telemetry generously given to us by Dr. Hock, [Hock99] and designed and built by NCAR. In the 2nd row at left is our previous generation DC-field mill, a single-axis device intended for ground deployment. You can see the two ground-blades, which spin and “chop” the E-field to enable DC measurements. The square board in the back middle is a full embedded PC with 8 channels of 100 kHz data acquisition designed to operate down to –40C. The small board at right is a last-generation GPS receiver with integrated antenna. This gives an idea of how much instrumentation needs to be shrunk to ultimately achieve the dropsonde form-factor.

The field-change plates and electronics also need to be fit, and are not shown in the photo, as we have never built one like what is described here. Likewise, the telemetry system is not shown.

Figure 5 indicates a method of interpreting data from the field-change meter. Consider a simplified model in which a leader travels at a constant velocity along a straight line depositing a uniform line charge density (charge per meter) behind its tip. Further, assume that the electrostatic approximation holds [Kasemir60], in which the distance from the field-change meter to the region of accelerating particles is smaller than the wavelengths of radiation that correspond to the frequency response of the instrument. Then, a field-change meter vertically above the path of a horizontal leader traveling along the x-axis would record a sequence of vectors such as those in figure 5.

In figure 5, the tails of the vectors are together at the origin and some of the vectors have times in milliseconds at their tips. The calculations use a leader velocity of 10⁵ m/s from left to right in the positive x direction, a positive line charge density of 10⁻³ C/m, and a distance of 1000 m from the instrument to the closest point on the line. These numbers are reasonable for stepped leaders traveling to ground [Uman01].

When the leader tip is far away before passing the instrument, the magnitudes of the vectors are small. When the leader tip is closest to the instrument and passing it (at time 0 in fig. 5), the x-component of the field is a maximum. When the leader tip is far away after passing the instrument, the z-component is maximum. Were the charge only at the leader tip, the field would go from primarily along positive x to mostly along –x, rather than stabilizing at +z. Space does not permit a figure, but these two cases could be readily distinguished. All vectors in figure 5 are in the first quadrant of the (x,z) coordinate system. For negative charge traveling to the right, all vectors would be in the third quadrant. For a positive (negative) charge traveling to the left, the vectors would be in the second (fourth) quadrant. Thus the time-varying pattern of vectors at the field-change instrument gives the sign of the charge and the direction of travel of the leader. The magnitudes of the vectors give the amount of charge per unit length when combined with the location of the leader channel from the lightning mapping array and the location of the instrument from its GPS receiver.

Unclarified in all this is the presumed existence of an LMA, a new, rare, and precious device. A “compact LMA” (with 10 us time resolution) has been set up near our Langmuir laboratory. I will focus the experiments at this site.
REFERENCES


