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ELECTRIC FIELD MILL NETWORK PRODUCTS TO IMPROVE DETECTION OF THE LIGHTNING HAZARD

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ABSTRACT
An electric field mill network has been used at Kennedy Space Center for over 10 years as part of the thunderstorm detection system. Several algorithms are currently available to improve the informational output of the electric field mill data. The charge distributions of roughly 50% of all lightning can be modeled as if they reduced the charged cloud by a point charge or a point dipole. Using these models, the spatial differences in the lightning induced electric field changes, and a least squares algorithm to obtain an optimum solution, the 3-dimensional locations of the lightning charge centers can be located. During the lifetime of a thunderstorm, dynamically induced charging, modeled as a current source, can be located spatially with measurements of Maxwell current density. The electric field mills can be used to calculate the Maxwell current density at times when it is equal to the displacement current density. These improvements will produce more accurate assessments of the potential electrical activity, identify active cells, and forecast thunderstorm termination.

INSTRUMENT DESCRIPTION
Figure 1 is a map of the electric field mill locations. The network consists of 34 sites of which 31 are continuously active. The individual sensors measure the vertical electric field in the range of ±15 kV/m with typical errors of 10% or better [Jacobson and Krider, 1976]. The data are digitized at a rate of 1 sample per second with a resolution of 30 V/m. The digitized data are computer analyzed in real-time and stored on magnetic tape for future research. The instruments, the data acquisition system, and various scientific applications of the data have been described previously by Jacobson and Krider [1976], Livingston and Krider [1978], Piepgrass et al. [1982], Krider and

INTRODUCTION
Kennedy Space Center and the Eastern Space and Missile Center have jointly operated an electric field mill network since 1975. The data are analyzed and used in real-time as an integral part of the lightning detection and warning system for the Kennedy Space Center and the Cape Canaveral Air Force Station area. The data collected has made valuable contributions to atmospheric electricity research and improved techniques for evaluating the electrical hazard. Over the past 10 years researchers have used techniques which provide more accurate information from the electric field mill network in locating the centers of the lightning activity. One technique is used to find the charge centers affected by lightning flashes. The software improvements, enabling the Space Center to use this technology in real-time, are currently being implemented. Additional products, under research, will help locate horizontally regions of peak charge movement. These regions are thought to be responsible for charge separation occurring within the cloud, during the initial and mature stages of thunderstorm formation. This technique will also be discussed and if proven reliable will be used for operations.
FIELD CHANGE ANALYSES

To provide both accuracy and rapid data processing, a computer algorithm very similar to that devised by Piepgrass et al. [1982] is used to identify lightning events. First, there is a coarse search for a field discontinuity in successive 1-s intervals, and then, when a discharge is detected, there is a careful determination of the flash time and the field change value at each site. The data for each site is first arranged into consecutive 1-s blocks, and the initial field in two adjacent blocks forms a linear projection used to extrapolate the expected field at the start of the third block. The projected field is then compared with the actual measured field, and the process continues until there is a difference of at least ±350 V/m at two or more sites. When such a discontinuity is detected, the field derivative is computed in 0.1 s intervals at each site, and the flash time is determined. The flash time is defined to be the average of the times of the five largest field derivatives of the entire network.

In order to determine the beginning and ending times of the flash as accurately as possible, the five sites that produced the largest field derivatives are examined for the times that the fields derivatives first deviated and then returned to a steady value. These times are found by searching backward and forward in 0.1 s steps from the flash time to the times when the field derivative has stabilized to values less than 1750 V/ms. The total field change is defined to be simply the field value at the end of the flash minus the field at the beginning. After this procedure is completed, the presence of lightning is checked by verifying that the absolute value of the total field change is still at least 350 V/m at two or more sites and that there had not been a discharge within the previous 0.6 s.

Maier and Krider [1986] looked at 273 electric field changes from relatively small isolated storms. They found resulting errors in the calculation process in the range of 5% or 30 V/m whichever was larger. All field changes in this paper include all electrical processes of a discharge.

CHARGE DISTRIBUTION MODELING

Approximately 50% of the flashes which produce field changes greater than or equal to 1 kV/m at two or more sites can be fitted to one of two charge distribution models [Maier and Krider, 1986]. The charge altered by cloud-to-ground flashes can be described by a point charge model,

$$\Delta E_i = \frac{\Delta Q}{4\pi \varepsilon_0 R_i^3}$$

where,

$$R_i = (X - X_i)\hat{x} + (Y - Y_i)\hat{y} + H\hat{z}$$

is the three dimensional position vector from the measuring site to the charge; $\Delta E_i$ is the electric field change at site $i$; and $X_i, Y_i$ is the location of instrument $i$. $\Delta Q$ represents the charge deposited by the lightning flash and $X, Y$, and $H$ are the location of the charge prior to the lightning event. The charge altered by cloud discharges can be described by a point dipole model,

$$\Delta E_i = \frac{-1}{2\pi \varepsilon_0 R_i^3} \left( \frac{3H(P \cdot R_i)}{R_i^2} - P \right)$$

where,

$$P = P_x\hat{x} + P_y\hat{y} + P_z\hat{z}$$

is the three dimensional dipole moment; $\Delta E_i$ is the electric field change at site $i$; and $X_i, Y_i$ is the location of instrument $i$. $R_i$ is the three dimensional position vector of the dipole moment with respect to the measurement location.

The analysis procedure used is a least squares optimization method described by Jacobson and Krider [1976] and similar to that used by Krehbiel et. al. [1979]. Given a set of measured field changes at the ground, there is a search for the unknown parameters, $\Delta Q, H, X$ and $Y$ or $\Delta P, H, X$ and $Y$, that minimize the function

$$C^2 = \frac{1}{N_{\text{free}}} \sum_i \frac{(\Delta E_{mi} - \Delta E_{ci})^2}{\sigma_i^2}$$

where $\Delta E_{mi}$ and $\Delta E_{ci}$ are the measured
and calculated field change values at site i, σ is the measurement error at site i, and \( N_{\text{free}} \) is the number of degrees of freedom, i.e., the number of measurements \( N \) minus the number of unknowns being determined.

Each flash is fitted to both the point charge and the point dipole model. Two requirements must be met before one of the two solutions is accepted. First, one model must produce a \( C^2 < 10 \). If the first requirement is satisfied the model which produces the lowest \( C^2 \) is considered to be a good approximation of the charge transfer process. The other flashes which do not meet this criteria can not be described adequately by either model and are ignored.

MAXWELL CURRENT ANALYSIS

Krider and Musser [1982], Blakeslee and Krider [1984] and Krider and Blakeslee [1985], demonstrate the ability to use the electric field sensors to measure the Maxwell or total air-earth current density. The Maxwell current density is a solenoidal vector,

\[
v \cdot J_m = v \cdot (J + \frac{\partial D}{\partial t}) = 0
\]

where \( J \) is the electric current density produced by the motion of free charges and \( \frac{\partial D}{\partial t} \) is the displacement current density. \( J \) is derived from several sources primarily a component due to lightning, a component due to convection currents and a component proportional to the electric field. At times when the electric field is close to zero, the record is between lightning flashes and convection and precipitation currents are small, the Maxwell current density can be described by

\[
J_m = \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t}.
\]

During the times when the displacement current density is an adequate approximation of the Maxwell current density, the electric field mill sensors can be used to calculate and display the variations in the Maxwell current density over both space and time.

Blakeslee and Krider [1984] and Krider and Blakeslee [1985] demonstrate that the Maxwell current density for one storm varied over several orders of magnitude and slowly with time. The Maxwell current density reached a peak near the time of the maximum lightning rate and was symmetric about the peak. If this holds true for the majority of air-mass thunderstorms the end of the electrical activity can be determined by the characteristic shape of the Maxwell current density, after it has begun decreasing.

Figure 2 is a trace of the electric field and two Maxwell current sensors taken during a summer thunderstorm. The slope of the electric field at instances when there is no lightning, in the absence of rain, and when the electric field is close to zero can be used to calculate the Maxwell current density (these times are denoted by arrows in figure 2). Constraining the electric field to zero for calculation of the Maxwell current density requires that in all cases except the trivial situation where the electric field is zero and unchanging, the presence of lightning is a necessity. Without polarity reversals of the electric field at five minutes or more often, the Maxwell current density will be sampled too frequently to be of any use. Fortunately, during most storms the lightning rates are adequate enough to sample the Maxwell current density at least once in five minutes. This technique looks very promising for both detecting the primary areas of charge separation and determining the end of electrical activity, but the measurements are few and not thoroughly understood to provide a definitive answer concerning the usefulness of the data.

THUNDERSTORM CHARGE STRUCTURE

To understand the significance of the products discussed here, a rudimentary understanding of the thunderstorm charge structure is necessary. Thunderstorm charge distributions are difficult to measure, are highly variable in both space and time, and are scattered over large volumes. A general model has evolved to describe the thunderstorm charge structure [Malan, 1952 and Malan, 1963]. The model is simplistic, but is probably adequate in describing the predominant charge regions resident in smaller air mass thunderstorms. A large region of negative charge is centered between the -10 and the -30 Celsius isotherms. The largest region of the positive charge has been observed above the negative charge center. Often a secondary positive charge center is measured below the negative charge center and is
usually associated with the presence of precipitation. Anvils can carry ice crystals up to 100 kilometers, dispersing much of the upper positively charged cloud mass. Charge conservation and the immense volume generally occupied by the upper positive charge, require that the lower negative and positive charge regions, during the mature stage of thunderstorm formation, are relatively dense when compared with the upper positive charge center.

**CHARGE LOCATIONS**

There are several products that can be derived from the charge location data. The simplest output is a histogram of the number of lightning. The histogram should be updated every 5 to 10 minutes. In the cases of isolated storms, a significant decline in lightning rate usually signals the decline of a thunderstorm. In the presence of multiple storms, the information must be sorted by the individual storms to be meaningful. In figures 3, 4 and 5 the number of lightning events occurring within the last hour is given in a histogram on the right-hand side in number of events per each five minute interval.

The calculated charge and point dipole locations can be overlaid onto a map of the measurement area. Figure 3 is an example with several lightning flashes. The cloud-to-ground lightning are designated by the letter Q and the intracloud lightning are designated by the letter P. The plan view allows the observer to track the storm, to monitor area expansion of active lightning charge centers and to define radar cells as lightning producers.

The data can also be displayed as a height versus time cross-section (see figure 4). The level of the negative charge center is usually centered between -10 and -30 Celcius. This can be used to judge how accurately the algorithms are working. The upper positive charge center can be estimated by adding the height difference between the point dipole center and the point charge center, to the point dipole center. The probable positive charge center in figure 4 is located between 11 and 12 km. This method of estimating the upper positive charge center is an upper estimate of its position. The intracloud flashes involving the positive charge may interact only with the uppermost negative charge and/or may involve predominately horizontal charge movement. During one storms lifetime, part of which is shown in figures 3, 4 and 5, the majority of the cloud-to-ground lightning occurred as the positive charge center was descending. It is also interesting that the cloud-to-ground activity preferentially occurred during periods of lesser intracloud activity. The charge models will not be able to fit every flash. The charge distribution may be more complicated than the two simple ones we are using, or the flash may be too small. For this reason the user is also given the capability to contour the electric field changes over the network (see figure 5). The large complicated flashes are observed to occur toward the dissipating stages of the storm and sometimes occur over large expanses along the anvil. The areas of maximum field change may or may not correspond to areas of concentrated charge but will at least give the user a broad electrically active area to avoid.

**THE REGION OF CHARGE MOVEMENT**

Regions of charge movement can be located horizontally by contouring the Maxwell current as determined by the electric field mill network. The locations of peak Maxwell current density correspond to regions of charge movement and probably pinpoint the region of charge separation during the initial and mature stages of the thunderstorm. These are the regions around which the electrical processes are concentrated and may correspond to those regions of large vertical motions and for regions of large horizontal gradients in the vertical velocities.

The graphic which may prove to be most useful, is a time-section of the Maxwell current density. If the Maxwell current density is slowly varying and if the time from beginning to peak is approximately equal to the time from peak to end, this will be a valuable tool for forecasting the end of electrical activity. The method currently being used involves both storm climatology and absolute electric field values which usually overestimates the duration of the actual electrical hazard.

**DISCUSSION**
Krehbiel [1984] and Maier and Krider [1986] each presented a storm in which the upper dipole locations gradually varied over the lifetime of a storm. In contrast, the point charge solutions remain surprisingly constant with time. The point dipole locations initially increased altitude very early in the storms lifetime and then gradually descended throughout the remainder of the storms lifetime. The location of the point dipole centers and their rate of descent may be used in the future in establishing an estimate of the end of the electrical hazard. This tool will not help forecast the onset of electrical activity nor will it set the regional limits of the electrically active area. It detects only the centers of charge activity after lightning is present. The benefit is its ability to pinpoint the areas of concentrated electrical hazard.

The Maxwell current density will be used to monitor the electrical growth of the thunderstorm and forecast its end. Because the Maxwell current density varies over 4 to 5 orders of magnitude from fair to thunderstorm weather, it may also be used to detect the formation of an electrical cell, before the occurrence of lightning. The centers of peak Maxwell current density are thought to occur in the regions where the charge separation process is strongest. It has been suggested that charge separation occurs in those areas where the horizontal gradient of the vertical wind velocities is strongest. Research is on going and will determine whether the Maxwell current density is a reliable indicator of electrical growth and whether contours can accurately locate the region of charge separation.

REFERENCES


FIGURE CAPTIONS

Figure 1. A map of the 34 field mill site locations on Kennedy Space Center and Cape Canaveral Air Force Station.

Figure 2. a) Electric field mill trace for a two minute interval taken during a storm in 1984. b) and c) Maxwell current density traces from two instruments located approximately 40 feet apart for the same time period in a). The arrows signify the times at which the displacement current density can be accurately calculated.

Figure 3. A display example giving the horizontal location of the point charge solutions (Q) and the point dipole solutions (P) for the last hour. The number of lightning detected in five minute intervals for the last hour is given in the right most region of the display.

Figure 4. A display example plotting the altitudes of the point charge solutions (Q) and the point dipole solutions (P) for the last hour. The lightning count histogram is also given (see figure 3).

Figure 5. A display example contouring the electric field change due to the last detected lightning. The lightning count histogram is also given (see figure 3).
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