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VECTOR ELECTRIC FIELD STRUCTURE
INSIDE A NEW MEXICO THUNDERCLOUD

by

Hugh J. Christian, Jr.

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

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CHAPTER I

Introduction

The physics involved in the electrification of thunderstorms is not well understood. Complexities associated with the magnitude, intensity, and variability of thunderstorms are so overwhelming that only the simplest models are used to represent the thunderstorm field structure. Classically, a simple positive dipole has been used to describe the electrified cloud. This model generally places a +40 coul. point charge at 10 km. altitude, a -40 coul. charge at 5 km., and often an additional +5 coul. at the base of the cloud (Malan, 1963). This model cannot be expected to accurately describe the charge distribution or magnitudes within a real thunderstorm. It is simply a zeroth order statistical representation derived from years of ground based measurements. No corrections are made for possible changes in conductivity, for discontinuities in the conductivity, or for the presence of space charge between the charge centers and the ground.

Kasmir (1965) challenged Malan's model on the basis that it did not contain conductivity or space charge correction terms. Using continuity of charge flow arguments, he calculated that the lower negative center contains -340 coulombs. It seems that data is so inconclusive that not even the simplest model can be established.
Magaziner (1975) demonstrated the futility for determining the unique charge distribution inside a thunderstorm from ground based electric field measurements. From these considerations it seems essential that in situ measurements of thundercloud electric fields be made before any useful field structure model can be derived. Balloon data taken by Winn and Byerley (1975) indicate that in-cloud field measurements are essentially free of the perturbing influence of the ion producing earth.

On 12 August 1975 a Balloon Electric Field Sensor (or BEFS) was launched from Langmuir Laboratory, New Mexico into a rather violent thunderstorm. This instrument, which is described briefly in Chapter II and in detail in Christian (1975), measured the full vector electric field as it rose through the thundercloud. These field measurements are compared with altitude, temperature, radar, and ground based field measurements. The results of these analyses are presented in Chapter IV.

Several objectives led to the design and flight of the Balloon Electric Field Sensor. From electric field profiles, we hope to determine the altitude of the major charge regions. From thunder reconstructions (Few, 1975), one can possibly determine the physical extent of these charge regions. From ground based field measurements one might be able to determine the change in the electric moment caused by a lightning event. With just these three measurements, it seems possible to determine the location of major charge regions within a thundercloud, the physical size of these charge regions, and the
quantity and density of charge contained in these regions. The primary objective of this particular experiment was to determine the location and dimensions of a major thundercloud charge center. We also intended to deduce the quantity and density of charge contained in this center.

There has been much speculation on the existence of an electrical screening layer at the cloud-air boundaries. Hoppel and Phillips (1971), Brown, et al (1971) and Klett (1972), all predicted the concentration of space charge at the cloud boundary due to conductivity differences between cloudy and clear air. It is expected that the screening layer is characterized by the build-up of positive charge at the cloud bottom and negative charge at the cloud top. Aircraft measurements by Gunn (1955) indicate a field increase upon entering the thundercloud. Conductivity measurements by Rusk and Moore (1974) confirm that conductivity is decreased inside a cloud. It would thus seem that the existence of the charge screening layer is established, yet speculation continues. The BEFS has the capability of measuring the full vector electric field as it enters a cloud. These measurements should help establish the existence of a screening layer and also indicate the physical characteristics of the layer.

The electrical screening layer, if it exists, could profoundly affect the electrical dynamics of a thunderstorm. Redistribution of charge along the cloud boundary following a lightning discharge would change the apparent regrowth characteristics of the field. Charge distributed along the sides of the
cloud could increase horizontal field structure and enhance horizontal lightning propagation. Finally, a continuous supply of charge at the surface of a cloud together with the turbulent redistribution of this charge into the interior of the cloud, could modify the interior charge distribution and provide local field enhancement which seems necessary for lightning initiation.

Ground based measurements of electric field growth versus time following a lightning discharge indicate exponential recovery. Illingworth (1971) and others have predicted that this so-called "recovery curve" is produced by air conductivity outside the storm and by redistribution of space charge produced by surface point discharge. He concluded that the actual field recovery inside the cloud might be quite different. Winn and Byerley's (1975) field measurements inside thunderclouds tended to be linear rather than exponential.

The recovery curve characteristic is very important because it is governed by the regeneration and/or redistribution of charge at the charge center and by the redistribution of charge at the screening layer. Measurements of charge regeneration rates may provide a selectivity criterion between certain charge generation theories.

In conclusion, the goals for this project were to determine the location and magnitude of thunderstorm charge centers, to prove the existence and describe the characteristics of electrical screening layers, and to measure the electric field growth inside the cloud following lightning. Such data is
essential before proper interpretation of ground based data can be made and before a useful electrified cloud model can be established. In addition, in situ vector electric field measurements should provide information vital in the physical evaluation of the vast array of proposed charge generation mechanisms.
CHAPTER II

The Balloon Electric Field Sensor

2.1 Introduction

A detailed description of the Balloon Electric Field Sensor (BEFS) can be found in Christian (1973). This work also includes a history of previous in-cloud measurements of thunderstorm electric fields, a summary of the results, and an evaluation of the relative merits of each instrument. That discussion concluded that the assorted variations of electric field mills were the most useful sensors, and that the type of lifting vehicle and the integration of the sensor with the lifting platform are the most important influences on the reliability of the field measurements.

The BEFS, which might be called a spherical field mill, is a variation of the cylindrical field mill described by Kasmir (1972). It is an a.c. coupled instrument with which we indirectly determine the vector electric field by measuring the induced charge flow between symmetric conductors as these conductors change their orientation with respect to the external electric field. The BEFS minimizes several problems previously associated with in-cloud field measurements; but, in addition, it imposes several new constraints.

2.2 Physical Description

The Balloon Electric Field Sensor consists of a super-pressure
spherical balloon with a conductive metal coating on the outer surface, and the associated electronics package which is mounted inside the balloon. The metalized surface of the balloon is divided into four conducting regions that are electrically isolated from one another on the balloon surface (see Figure 1). Two of these lunar regions are symmetric about the vertical spin axis. The other two are symmetric about the horizontal axis.

These conducting quadrants serve as the sensing elements of the instrument. When the balloon is exposed to an electric field, charge is induced on these conducting surfaces. As the balloon changes its orientation with respect to this field, the induced surface charge is redistributed. A resulting induction current is measured as it flows through the wires connecting each symmetric lunar pair with electrometer circuits. Since the orientation of the balloon can be determined from on-board sensors, this induction current can be used to calculate the external vector electric field.

Again referring to Figure 1, notice that the spin paddles are mounted one on each side near the intersections of the quadrant separators. Their position, together with the location of the electronics package, determines the spin axis. Spin is caused by the torque imparted on the spin paddles as the balloon rises. While the rotational period of the balloon depends on the rate of rise, it is on the order of ten seconds.

The quadrant separators shown in Figure 1 serve both to maintain the
electrical isolation of the individual quadrants and to reduce rain shorting between quadrants.

A total of four relief valves are mounted on the balloon. Since the balloon is super-pressurized on the ground, the relief valves are necessary in order to allow for sufficient out-gassing during flight. The valves are set to maintain a positive pressure differential of 40 millibars inside the balloon.

In the present design the balloon is ten feet in diameter, displaces 524 cubic feet and can lift a five pound payload to 9.5 km.

2.3 Theory of Operation

As stated previously, the conducting lunes serve as the electric field sensing elements for the instrument. The balloon appears as a conducting sphere to a uniform electric field. This electrostatic problem has been treated in numerous texts (e.g., Stratton, 1941). A complete solution is worked out in Christian (1975). This solution shows that the induced surface charge density on the sphere is given by

\[ \sigma = 3\varepsilon_0 E_o \cos \theta \]  \hspace{1cm} (2.3.1)

where \( \sigma \) = surface charge density

\( \varepsilon_0 = \) permittivity of free space (8.85 x 10\(^{-12}\) \text{f-m})

\( \theta = \) angle between the ambient field and a point on the surface of the sphere.

If the electric field vector \( E_o \) is perpendicular to the normal at the
center of a conducting lune, then integrating over that lunal surface yields a
total induced surface charge of (Christian, 1975)
\[ Q = 3 \sqrt{2} \pi r^2 E_o \]
where \( r \) = radius of balloon.

Now, if the center of this particular quadrant is rotated to an
arbitrary angle \( \theta \) with respect to the field vector, then the induced surface
charge on that quadrant becomes (Christian, 1975)
\[ Q(\theta) = 3 \sqrt{2} \pi r^2 E \cos \theta \]

Obviously, when the orientation of each quadrant of the balloon
changes with respect to \( E_o \), the magnitude of the induced charge on that
quadrant must change. That is, for any \( \frac{d\theta}{dt} \) there will result a \( \frac{dQ}{dt} = I \). This
induced current is measured as it flows between symmetric quadrant pairs.
Once \( Q(t) \) is determined, \( E_o \) can be calculated.

Referring to Figure 2, we may redefine the direction cosine angle \( \theta \),
which is the angle between \( E_o \) and the center of the upper lune, in terms of two
angles \( \alpha \) and \( \beta \). Beta is the angle between the lunal intersection along the
positive X axis and \( E_o \). Alpha is the angle produced when \( \beta \) is projected onto
the Y-Z plane. Equation 3 then becomes
\[ Q_A = C' E_o \cos \alpha \sin \beta \]
where \[ C' = 3 \sqrt{2} \pi \epsilon_o r^2 \]
\[ \cos \theta = \cos \alpha \sin \beta \]
Equation 4 represents the total charge induced on the upper lune (quadrant A in Figure 1). It follows that the induced charge on the other three lunes in terms of $\alpha$ and $\beta$ is

$$Q_B = -C'E_0 \cos \alpha \sin \beta$$
$$Q_C = -C'E_0 \sin \alpha \sin \beta$$
$$Q_D = C'E_0 \sin \alpha \sin \beta$$

Differentiating Equation 2.3.4 with respect to time yields

$$I_A = C' \left[ \frac{dE}{dt} \cos \alpha \sin \beta + E(\cos \alpha \cos \beta \dot{\theta} - \sin \alpha \sin \beta \dot{\alpha}) \right]$$

Similarly, the rate of change of charge on the other three lunes is given by

$$I_B = -C' \left[ \frac{dE}{dt} \cos \alpha \sin \beta + E(\cos \alpha \cos \beta \dot{\theta} - \sin \alpha \sin \beta \dot{\alpha}) \right]$$
$$I_C = -C' \left[ \frac{dE}{dt} \sin \alpha \sin \beta + E(\sin \alpha \cos \beta \dot{\theta} + \cos \alpha \sin \beta \dot{\alpha}) \right]$$
$$I_D = C' \left[ \frac{dE}{dt} \sin \alpha \sin \beta + E(\sin \alpha \cos \beta \dot{\theta} + \cos \alpha \sin \beta \dot{\alpha}) \right]$$

Each symmetric lunal pair is connected together through differential charge amplifiers, as shown in Schematic 1 of Appendix B. The charge amplifiers integrate the current flowing between lunes. Figure 3 shows the frequency response of these amplifiers. When the balloon rotates with an angular velocity that corresponds to the band pass region of the charge amplifiers, their voltage output is independent of the rotational rate. The charge amplifier transfer function is then

$$V_o = -\frac{AQ}{C_F}$$
That is, the charge amplifier output voltage is proportional to the change in the induced lunar surface charge and inversely proportional to the feedback capacitor. Obviously, the amplifier gain is determined by the feedback capacitor.

When the balloon rotates too slowly, the output is no longer independent of the rotational rate (or frequency), and the transfer function becomes

\[ V_o = -\frac{AQ}{C_F} \left[ 1 + \left( \frac{1}{\omega R_F C_F} \right)^2 \right]^{-1/2} \]  \hspace{1cm} 2.3.7

Equation 2.3.7 reduces to 2.3.6 for \( \omega R_F C_F \gg 1 \).

Using Equation 6 for simplicity, we see that as the balloon rotates between two angles, the redistribution of surface charge will result in the voltage output from a lune to be

\[ V_2 - V_1 = -\frac{C'_F E}{C_F} (\cos \theta_2 - \cos \theta_1) \]  \hspace{1cm} 2.3.8

In terms of Equation 4

\[ V_{A_2} - V_{A_1} = -\frac{C'_F E}{C_F} (\cos \alpha_2 \sin \beta_2 - \cos \alpha_1 \sin \beta_1) \]
\[ V_{B_2} - V_{B_1} = \frac{C'_F E}{C_F} (\cos \alpha_2 \sin \beta_2 - \cos \alpha_1 \sin \beta_1) \]
\[ V_{C_2} - V_{C_1} = \frac{C'_F E}{C_F} (\sin \alpha_2 \sin \beta_2 - \sin \alpha_1 \sin \beta_1) \]
\[ V_{D_2} - V_{D_1} = -\frac{C'_F E}{C_F} (\sin \alpha_2 \sin \beta_2 - \sin \alpha_1 \sin \beta_1) \]  \hspace{1cm} 2.3.9

The outputs from the paired vertical and horizontal charge amplifiers \((V_A, V_B, V_C, V_D)\) are then fed to the summing amplifiers, and finally to
compression amplifiers. The summing amplifiers output a voltage representing the difference voltage between each charge amplifier pair. The compressor amplifiers provide a specified gain for a final output voltage. The two final outputs are given by

\[ V_{V_x} - V_{V_y} = - G \ E (\cos \alpha_2 \sin \beta_2 - \cos \alpha_1 \sin \beta_1) \]

\[ V_{H_x} - V_{H_y} = - G \ E (\sin \alpha_2 \sin \beta_2 - \sin \alpha_1 \sin \beta_1) \quad 2.3.10 \]

where \( G = 8 \cdot \frac{C'}{C_F} = 1.096 \times 10^{-4} \) m

for compressor amp gain (in range one) = 4

\[ C' = 3 \cdot \frac{\sqrt{2}}{2} \pi \varepsilon_0 r^2 = 1.37 \times 10^{-10} \ f \cdot m \]

\[ C_F = 10 \mu f \]

Equation 2.3.10 specifies the output voltage from the vertical and horizontal sensors, resulting from a change of balloon orientation with respect to a uniform external electric field.

2.4 Modes of Operation

2.4.1 Field Mill Mode

In the last section we saw how a balloon orientation change with respect to a uniform electric field causes a redistribution of surface charge which is detected as a voltage output. This is the principal operational mechanism and will be referred to as the field mill mode. As mentioned previously, balloon motions about the Z-axis (spin) and about the X and Y axes (wobble) are measured by on-board sensors and are used together with the
electrometer output voltage in calculating the vector electric field. This procedure is detailed in Chapter III.

There are three additional operating modes through which the instrument senses its electrical environment.

2.4.2 Gradient Electric Field Mode

If the electric field magnitude changes with altitude in a region through which the balloon is rising, the induced charge on the vertical surfaces redistributes as follows:

\[
\frac{dQ}{dt} = \frac{d}{dt} \left( C' E \cos \theta \right) = C' \frac{dE}{dt} \cos \theta = C' \frac{dE}{dz} \frac{dz}{dt} \cos \theta
\]

\[
\frac{dQ}{dt} = C' W \hat{E}_r
\]

where \( W \) = vertical velocity of the balloon.

This charge flow results in an output voltage given by

\[
V_V = 8 C' R_F W \hat{E}_V = 193 W \hat{E}_V
\]

where \( R_F \) = Feedback resistor = 220 kΩ.

In this mode (because of the low frequency content) the current tends to flow through the feedback resistor rather than the feedback capacitor. The charge amplifier acts as a current-to-voltage converter rather than an integrator. The output produced by a gradient electric field appears as a d.c. offset voltage.
2.4.3 Contact or Rain Current Mode

When the balloon collides with charged hydrometeors, a d.c. contact current will flow between the upper and lower lunes; also, between the horizontal lunes of the balloon, if the balloon has a net rotation about the Y-axis. This contact current produces an output similar to that produced by the gradient field mode and can be distinguished only after simultaneous fits of the field parameters to all the sensor modes.

Considering only balloon motion, the contact current is equal to the net hydrometeor charge density times the rise velocity times the vertical quadrant cross-sectional area. That is,

\[ I_C = \rho \ W \ A \]

The resulting output voltage is

\[ V_C = 8 \ R_F \ \rho \ W \ A = (9.1 \times 10^6) \ W \rho \]

\[ \rho = \text{Charge density (coul/m}^3\text{)} \]

Rather than the contact current being caused by the BEFS’ vertical motion, it could be caused by the fall of charged hydrometeors. In this case the BEFS measures a rain current, and the output voltage is given by

\[ V_C = 2 \ G \ R_F \ I_C = 2 \ G \ R_F \ J_R \ A = (9.1 \times 10^6) \ J_R \]

where \( J_R \) = Rain current density (amp/m\(^2\))

The BEFS probably senses only rain current density rather than true space charge density because small drops tend to follow the streamline flow around the balloon rather than striking the conducting surface. Langmuir and Blogett
(1946) calculated the collection efficiencies of spheres as a function of drop size and velocity. Their results indicate the BEFS will generally only collide with drops greater than 200 microns in diameter.

One must be very deliberate in interpreting "contact current" because with the present design it is impossible to distinguish whether a positive offset voltage is caused by positive charge entering the upper sensor or by negative charge leaving the bottom sensor.

2.4.4 Electric Field Change Mode

In the final sensing mode, the BEFS acts as a dual field change meter. Upon the field collapse associated with a lightning discharge, charge is rapidly redistributed on the balloon surface. The sensor output voltage is characterized by a rapid voltage change followed by an exponential decay with \( R_F C_F \) time constant. The governing field change equation is:

\[
\Delta V = 2 \frac{G}{C_F} (\Delta Q) = 2 \frac{C'_F}{C_F} \Delta E \cos \theta \\
= (1.096 \times 10^{-4}) \Delta E \cos \theta
\]

The time dependence of the voltage change is not in general related to time required for field collapse. Rather, the initial voltage rise rate is determined by \( R_C C_C \) and the decay by \( R_F C_F \).

The voltage output in the field change mode is easily distinguished from outputs due to other sensing modes. The field change data, which does not
depend on balloon motion, provides very useful information on the electric field orientation and charge transfers. An analysis of field change data is presented in Chapter III.

2.5 Electronics Package

This section contains only a brief description of the BEFS electronics package. A more detailed description is available in Appendix B. Figure 4 shows a block diagram of the electronics system.

Referring to Schematic I of Appendix B, we see that $R_C$ and $C_C$ form a low pass filter and prevent any Nyquist folding problems. The charge and difference amplifiers act as described in the last section. The compression amplifier uses a non-linear transfer function that effectively increases the overall dynamic range of the field sensing system. It accomplishes its compression by decreasing the gain on any voltage above a certain limit. The gain response of this amplifier is shown in Figure 5.

The output voltage from each compressor amplifier is sampled every 1.92 msec by a 16 channel analog multiplexer. At the same time, auxiliary data from a pressure transducer, orthogonal magnetometers, orthogonal inclinometers and external and internal thermistors are fed to the analog multiplexer and each are sampled every 7.68 msec. From the multiplexer, the data is fed through a sample/hold amplifier to a twelve bit analog-to-digital converter. The digitized data, which is encoded in either bi-phase or non-return-to-zero
(NRZ) formats, then frequency modulates a 1680 MHZ solid state transmitter which drives a surface mounted, cavity backed, spiral antenna.

The two hall effect magnetometers are mounted along the X and the Y balloon axes respectively (see Figure 6). The magnetometers are used for determining balloon azimuth with respect to magnetic north.

One inclinometer is mounted along the balloon X-axis; the other is mounted along the Y-axis. The inclinometers measure balloon rotations about the X and Y axes, and hence the balloon polar angle with respect to gravity.

The pressure transducer measures the pressure profile inside the thunderstorm and serves as an altitude indicator. The external thermistor measures the temperature profile (see Figure 22), while the internal thermistor supplies housekeeping data. Because of its metallic coating, the balloon is easily tracked by radar except in the most intense rain regions. The 1680 MHZ transmitter also allows tracking by a standard meteorological rawinsonde receiver (GMD). With all the auxiliary sensors, not only can the BEFS experiment measure the vector electric field inside a thundercloud, but it can also supply information on the storm's temperature, pressure and wind structure.

On a final note, the combination of the twelve bit A/D conversion and the compressor amplifiers gives the instrument tremendous dynamic range. In its present configuration, the field meter is capable of resolving one part in $2 \times 10^6$. This 86 db dynamic range is necessary because of the large variation in
thunderstorm field magnitudes and because of the unreliability of balloon wobble which is necessary for field determination.

2.6 Balloon Orientation

As already mentioned, balloon orientation is determined using two orthogonal magnetometers and two orthogonal inclinometers. Figure 7 shows the series of four rotations, two about the Y axis and one each about the X and Z axes, used in transforming from a magnetic field aligned coordinate system, to a balloon based coordinate system. These rotations, while not the classical Euler types, were chosen for compatibility with orientation sensor type and location, and for the resulting simplifications in the data reduction equation.

The full matrix transformations are presented and solved in Appendix A. The procedure is outlined here. Referencing Figure 7, we see that the first transformation is a positive rotation about the Y axis. This rotation transforms the coordinates from a magnetic field aligned system to an earth based system. In this earth based coordinate system, the X axis points toward magnetic north and the Z axis points away from the earth's center. Obviously $\theta'$ is the local magnetic dip angle.

The second transformation consists of a positive rotation about the Z axis. This rotation determines the azimuth angle $\phi$; that is $\phi$ becomes the angle between magnetic north and the X axis of the balloon. Because the magnetometer outputs are inverted when amplified, the positive rotation
actually results in the calculated values of $\varphi$ to increase clockwise and yield the standard compass orientation.

The third and fourth transformations consist of negative rotations about the $X$ and $Y$ balloon axes respectively. These rotations, which are measured directly by the on-board inclinometers, uniquely determine the polar inclination of the vertical lunes. The rotation angle $\alpha$ about the $Y$ axis is a measure of inclination of the horizontal lunes with respect to earth normal.

It should be emphasized that this series of transformations does not uniquely determine the orientation of the balloon in space. This is because there is no preference in the rotational order about the $X$ and $Y$ axes. This procedure does, however, provide us with a mechanism for the determination of the orientation of an external electric field both with respect to the balloon and with respect to the earth reference frame. This system works nicely because the orientation of the vertical lunes is uniquely determined and because only rotation about the $Y$ axis affects the induced charge on the horizontal lunes. This discussion will be continued in Chapter III.

Appendix A shows that after solving the matrix transformation resulting from the four rotations, the equations reduce to:

$$\sin \varphi = -\frac{\cos \chi \sin \beta - \sin \chi \cos \beta \cos \theta}{\cos \beta \sin \theta}$$

2.5.1

Where $\varphi$ = Balloon azimuth angle with respect to magnetic north
\[
\cos Y = \text{Direction cosine between the Y axis magnetometer and the magnetic field lines (} = \frac{V_Y}{B_Y}); \text{ where } V_Y = Y \text{ magnetometer output voltage and } B_Y = \text{magnetic field magnitude times a calibration factor (i.e., } B_Y = G_Y B_0)\]

\[
\beta = \text{Balloon angular rotation about its X axis. This angle is measured directly by the X axis inclinometer.}\]

\[
\theta' = \text{Magnetic field dip angle.}\]

If we now reverse the order of the final two rotations, that is, rotate first about the Y axis and then about the X axis, the transformation equations reduce to:

\[
\cos \varphi = \frac{\cos X \cos \alpha + \sin \alpha \cos \theta'}{\cos \alpha \sin \theta'} \tag{2.5.2}
\]

where \(\cos X\) = Direction cosine between the X axis magnetometer and the magnetic field lines (\(= \frac{V_X}{B_Y}\)); and \(B_X = G_X B_0\)

\[
\alpha = \text{Balloon angular rotation about its Y axis. This angle is measured directly by the Y axis inclinometer.}\]

Combining equations 2.5.1 and 2.5.2 yields:

\[
\varphi = \tan^{-1} \left[ - \frac{G_X}{G_Y} \frac{\cos \alpha}{\cos \beta} \left( \frac{V_Y + G_Y \sin \beta}{V_X + G_X \sin \alpha \cos \theta'} \right) \right] \tag{2.5.3}
\]

Since \(\theta'\) is known at a given locale, \(\alpha\) and \(\beta\) are measured and \(G_X\) and \(G_Y\) are determined in the lab, equation 2.5.3 can be used to determine azimuth at all times during the flight.

Balloon inclination from vertical is determined simply from:

\[
\cos \theta = \cos \alpha \cos \beta
\]

or \[
\theta = \cos^{-1} (\cos \alpha \cos \beta) \tag{2.5.4}
\]

where \(\theta\) = Balloon polar angle.
2.7 Design Criteria

The unusual design of the BEFS is a result of difficulties involved in measuring vector electric fields inside thunderclouds. Intense fields, low conductivity and high turbulence are common in thunderstorms. Under these conditions, instruments have trouble surviving, much less making accurate field measurements.

Two major problems encountered during previous thundercloud field measurements have been associated with system calibration and corona discharge. Any conductor, when exposed to an electric field, will distort that field. The degree of distortion, known as the enhancement or form factor, must be determined before accurate field measurements can be made. For this reason, the sensing instrument and its lifting platform must be calibrated in the presence of known electric fields. In the case of aircraft, the calibration can be a very complex procedure. The accuracy of standard procedures is very questionable.

The BEFS spherical geometry permits the enhancement factor to be calculated directly from theory. No sensor calibration is required. The system enhancement factor is as accurate as the balloon construction. Errors are on the order of a few per cent.

Another major error source is corona current initiated at the sensing vehicle. Thunderstorms produce very intense electric fields. If these fields are further enhanced by the presence of conductors, corona discharge may be
initiated. Greatest field enhancements occur along elongated or pointed conductors. Aircraft wing tips and edges are excellent examples of areas of large field enhancements. When corona discharge occurs, the ambient electric field is strongly distorted and accurate field measures are impossible.

Great care was taken in designing the BEFS to reduce the onset of corona current. The spherical shape of the BEFS minimizes this problem since a sphere produces the smallest possible enhancement factor (equal to 3) in an electric field. By mounting the electronics package inside the balloon and by eliminating all protruding conductors, the instrument shows only a single smooth, large diameter surface to an electric field. With these design innovations, the BEFS should be capable of accurately measuring stronger electric fields than other systems.

With many balloon-borne experiments, static charge build-up on the surface of the balloon distorts the ambient electric field. When static charge builds up on the BEFS, it becomes evenly distributed and does not affect field measurements which are determined from changes in balloon orientation with respect to the external field. Other benefits are that the metallized surface reduces system weight since no external electrodes are required. It also acts as an electric shield, protecting the internal electronics from the noise spikes of lightning discharges.
2.8 Design Limitations

Every design has certain liabilities. An unfortunate design consequence of the BEFS is the slow balloon spin rate and the reliance on balloon wobble. These are important considerations since the spin of the balloon is used in determination of the direction and magnitude of the horizontal component of the electric field and wobble is used to determine the inclination of the field vector.

Problems occur during lightning discharges because of the long RC time constant required to compensate for slow balloon spin rates. The step function caused by a lightning discharge decays with a 2.2 second time constant. During this time it is difficult to separate the effects of the step function decay from any field recovery. This problem is particularly acute during periods of high lightning activity and low spin rates.

Balloon wobble is caused by the weight distribution, torque points and self-induced motion of the balloon and by the effects of local turbulence on the balloon. Balloon wobble is required for determining the total field magnitude. It was found that the balloon tended to wobble through smaller angles than originally anticipated and proved to be an unreliable motion. A solution to this problem is discussed in Chapter V.

Reduction of the resistance between lunes due to rain shorting was investigated as a potential error source in Christian (1975). It was shown that with the charge amplifiers (which present a small input impedance to the
system) and the rain separators (see Figure 1), rain shorting would produce a negligible error.

Voltage outputs produced by the flow of true conduction currents through symmetric lunes was also investigated as a potential error source. It was shown that errors produced by true conduction currents in the thunderstorm environment would be very small because of the reduced conductivity in thunderclouds (Rusk and Moore, 1974).
CHAPTER III

Data Analysis

3.1 Introduction

Analysis of the data recorded during the 12 August 1976 flight has been difficult. Problems occurred whenever the inclination of the field vector or balloon wobble was small and whenever contact currents were large. These problems in particular often caused large error bars to be associated with calculating the total field magnitude. Additional problems occurred whenever lightning activity increased or spin rate slowed.

3.2 Horizontal Curve Fit

3.2.1 Governing Equation

The principal technique we used to reduce the raw data was to curve fit the horizontal lunal output to an equation that compensated for the balloon orientation with respect to an assumed electric field direction. From part a of Figure 8, we see that for a given electric field polar angle $\theta$ and azimuth angle $\phi'$, we can determine the direction cosine angle $\theta'$ from the electric field vector to the balloon's X axis (which is the center of the positive horizontal lune), if we know the balloon's azimuth and the rotation ($\alpha$) about its Y axis. (For this derivation we assume that there is no rotation about X
axis.) From spherical trigonometry,

\[
\cos \theta = \cos \xi \cos (90 - \theta) + \sin \xi \sin (90 - \theta) \cos (90 - \zeta)
\]

\[
= \cos \xi \sin \theta + \sin \xi \cos \theta \sin \zeta
\]

where angles are defined in Figure 8.

Now from the law of sines,

\[
\frac{\sin \zeta}{\sin \alpha} = \frac{\sin 90}{\sin \xi}
\]

or \[\sin \zeta = \frac{\sin \alpha}{\sin \xi} \]

\[\therefore \cos \theta = \cos \xi \sin \theta + \cos \theta \sin \alpha \]

Note that \[\cos \xi = \cos \phi \cos \alpha \]

Then \[\cos \theta = \cos \phi \sin \theta \cos \alpha + \cos \theta \sin \alpha \quad 3.2.1 \]

This equation holds exactly when \( \beta \), the rotation angle about the \( X \) axis is zero. For \( \beta \neq 0 \), we refer to part B of Figure 8 and solve for a new \( \xi \).

\[
\cos \xi = \cos \phi \cos \alpha + \sin \phi \sin \alpha \cos (90 + f \beta)
\]

\[
= \cos \phi \cos \alpha - \sin \phi \sin \alpha \sin (f \beta)
\]

where \( f \) is that portion of \( \beta \) rotation that occurs prior to the \( \alpha \) rotation.

Now \[\frac{\sin \alpha}{\sin \zeta} = \frac{\sin \xi}{\sin (90 + \beta)} \]

or \[\sin \zeta = \frac{\sin \alpha \cos (f \beta)}{\sin \xi} \]

\[\therefore \cos \theta = \cos \xi \sin \theta + \sin \xi \cos \alpha \sin \theta \cos \alpha \cos (f \beta)
\]

Then \[\cos \theta = \cos \phi \sin \theta \cos \alpha + \cos \theta \sin \alpha \cos (f \beta) - \sin \phi \sin \theta \sin \alpha \sin (f \beta) \]

where \( 0 \leq f \leq 1 \) and \( \langle \vec{f} \rangle = \frac{1}{2} \)

Hence \[\cos \theta = \cos \phi \sin \theta \cos \alpha + \cos \theta \sin \alpha \cos \left( \frac{\beta}{2} \right) - \sin \phi \sin \theta \sin \alpha \sin \left( \frac{\beta}{2} \right) \quad 3.2.3 \]
This equation determines the direction cosine between the electric field vector and the center of the horizontal lune. Estimating the value of $f$ is necessary because our transformation system does not establish an order for rotations about the $X$ and $Y$ axes. This is of little consequence since both $\alpha$ and $\beta$ tend to be very small ($< 10$) and since the effect of $\beta$ in equation 3.1.3 is very weak. It has only a second order effect and equation 3.1.2 can generally be used. Further, since rotations about the $X$ and $Y$ axes are equally probable, $f$ will average to $1/2$.

Recalling 2.3.10, we see that $\cos \theta$ may be substituted for the angular dependence. Then,

$$V_H = kE \left( \cos \theta_2 - \cos \theta_1 \right)$$  \hspace{1cm} 3.2.4

If $\theta_1$ is chosen when $\theta$ is equal to $90^\circ$, then 3.1.4 reduces to

$$V_H = kE \cos \theta$$  \hspace{1cm} 3.2.5

The spinning motion of the balloon insured that $V_H$ goes to zero at least twice each rotation. This is obvious from equation 3.2.1 when we assume no wobble. Then,

$$V_H = kE \cos \phi \sin \theta = kE_H \cos \phi$$

where $E_H = \text{Horizontal component of the electric field}$

The horizontal voltage output is modulated by the balloon spin. The output due to spin is sinusoidal. Superimposed on this spin produced output is modulation due to wobble, especially about the $Y$ axis.

Equation 3.2.5 indicates that the electric field magnitude can be
determined from the horizontal output if the electric field polar angle \( \theta \) and azimuth angle \( \phi' \) are known. For simplicity we now substitute values from equation 3.2.1 for \( \cos \theta' \), even though in the actual analysis equation 2.3.2 was used. Equation 3.2.5 then becomes

\[
V_H = K E \left( \cos \varphi \sin \theta \cos \alpha + \cos \theta \sin \alpha \right)
\]

or

\[
E = V_H \left[ K (\cos \varphi \sin \theta \cos \alpha + \cos \theta \sin \alpha) \right]^{-1}
\]

where \( \varphi \) is the angular difference between the balloon azimuth and the electric field azimuth \( \phi' \).

3.2.2 Curve Fit Program

Initially we know neither \( |E| \), \( \theta \) nor \( \varphi \), but by using a curve fitting technique, all can be determined to certain accuracies. Phi is rather easy to determine since \( V_H \) increases to its maximum as phi goes toward zero. Theta is difficult to determine. Once theta and phi are determined, \( E \) can be calculated using equation 3.2.6.

A curve fitting program was used to simultaneously solve for the three unknowns using equally spaced data points governing specific time periods. Typically a ten second time period was used for each fitting because this corresponded to the balloon rotational period. Initially an operator assumes a theta and phi. The computer then uses these assumed angles to solve for \( E \) in equation 3.2.6. One \( E \) value is returned at each data point during the time interval. Once the array of electric field values is calculated, the computer uses a least-squares, linear fit routine (Bevington, 1969) to generate a second array of electric field values. This second array of fitted values represents the
best straight line fit to the calculated electric field values. A non-reduced chi-square is then calculated in order to establish a goodness of fit criteria between the calculated and the fitted values.

Once a first chi-square value is calculated, a grid search through phi space is initiated. The search is terminated with a polynomial fit to determine best phi.

After phi is determined, a theta search is initiated. During the theta search, phi is held constant and theta is varied until a minimum chi-square is calculated. The search is again terminated with a polynomial fit determining optimum theta. Finally both theta and phi space are each searched a second time using a finer grid.

Using this curve fit/grid search technique, the best fitting vector electric field is determined from horizontal voltage data and from balloon orientation data. This technique tacitly assumes that the field does not change its orientation during a given time period and that any changes in field strength are relatively linear. These assumptions are generally reasonable except for when lightning discharge occurs. Fortunately the evaluation periods can be varied so that the effects of lightning discharges are reduced.

Another important point is that our assuming linear field strength increases for the curve fit process does not necessarily result in errors in the theta and phi determination. For example, if the field increased exponentially,
it would result in a poor fit but not necessarily in erroneous theta and phi. This is because the phi fit, using balloon spin, determines the direction of the horizontal component of E and the theta fit, using balloon wobble, determines the vertical inclination of E. Neither fitting process is directly concerned with the magnitude of E. If field magnitude did change in a non-linear fashion during a given time period, it is unlikely that an associated periodicity would be the same as either the spin or wobble periods. In such a case, the linear fit process would result in a poor fit but accurate theta and phi. To further support this argument we made computer plots of the calculated electric field values and of the fitted electric field values for each time segment. In no case were any obvious non-linear field growth characteristics observed to invalidate the fitting procedure. The resulting theta and phi seemed reasonable. We have dwelled on this subject because the reader must be insured that calculating a linear fit to the data does not linearize the data.

3.2.3 Error Sources

Typically the reduced chi-squares values were less than 0.03. This corresponds to a probability of better than 99 per cent that the fitted values were statistically related to calculated field values. Fits were not always good. Biggest problems were associated with balloon wobble and small electric field polar angles. Wobble was the sole mechanism used to determine field inclination. Unfortunately, balloon wobble was far below expectations, probably due to low initial free lift. With insufficient wobble about the Y axis, the
fitting procedure became rather insensitive to changes in theta. That is, changing theta over fairly wide ranges produced only small changes in chi-square values. When this occurred, truly accurate determinations of the polar angle and the total field magnitude could not be made. In these cases we assumed that theta changed smoothly with time and folded in values from earlier and later times where theta was accurately determined. Judging from the resulting profiles and from the apparent long localization of the charge centers, this was probably a good assumption. A plot of theta versus time is shown in Figure 17.

Overall theta is probable accurate to ± 10 degrees. For large polar angles, a ten degree error in theta would produce errors of only a few per cent in calculating the total field magnitude. However, at small polar angles, a ten degree theta error could theoretically result in a hundred per cent error in calculating the total field magnitude.

Using the curve fit technique, phi is determined to within ± 5 degrees. Errors in phi contribute little to other calculations. Phi versus time is shown in Figure 18. The horizontal component of the electric field, plotted in Figure 15, is accurate to approximately ten per cent except during periods of very slow spin rates or high lightning activity. As previously mentioned, lightning discharges caused problems because of long charge amp time constants.

Errors involved in calculating the total electric field strength are probably 20 per cent. These errors occur mainly from inaccuracies in
determining theta. Figure 16 shows the total field strength as a function of
time measured during the 12 August 1975 flight.

3.3 Vertical Fitting Technique

Because the charge induced on the vertical lunes is not spin
modulated, the vertical voltage output has proven to be not as useful for field
determination as the horizontal output. Yet the vertical output supplied
excellent independent data for calculating field strength especially for large
thetas.

The induced charge on the vertical lunes is modulated by balloon
wobble about its X and Y axes. Referencing Figure 9, we see that the total
induced charge on the vertical lunes is

\[ Q = GE \cos \theta \]

where \( \cos \theta = \cos \beta \cos (\theta + \alpha) \)

or \( \theta = \sqrt{(\theta + \alpha)^2 + \beta^2} \)

This equation holds only for a zero azimuth angle between the field vector and
the balloon. For an arbitrary azimuth angle \( \phi \),

\[ \theta = \left[ (\theta + \alpha \cos \phi + \beta \sin \phi)^2 + (- \alpha \sin \phi + \beta \cos \phi)^2 \right]^{1/2} \]

where \( \theta = E \) field polar angle

\( \alpha, \beta = X, Y \) rotations

3.3.1

Then, from equation 2.3.10

\[ V_v - V_v = KE (\cos \theta_2 - \cos \theta_1) \]
where \( V_Y = \) Output voltage difference between vertical lunes

And again,

\[
E = \frac{V_{V_2} - V_{V_1}}{K (\cos \theta_2 - \cos \theta_1)}
\]

3.3.2

Unlike equation 3.2.6, it is necessary to use voltage differences in this case because the vertical induced charge is not fully modulated and because d.c. offset voltages can occur.

Whenever the computer solved for theta and phi using the curve fit routine, it also calculated a corresponding array of gammas using equation 3.3.1. Once the gammas are calculated, it is relatively easy to solve for \( E \) in equation 3.3.2. Generally these calculations are done by hand since arbitrary selection of data points usually results in dividing a small voltage difference by a small angular difference and thus results in large errors. If \( \theta_1 \) and \( \theta_2 \) in equation 3.3.2 are selected at points where the balloon inclination changed from a minimum to a maximum, then relatively accurate calculations of \( E \) can be made. This procedure provided important collaborating data and provided confidence in the accuracy of our solutions for the vector electric fields.

3.4 Field Change Analysis

As described in Section 4 of Chapter II, the BEFS acts as a dual field change meter, rapidly sensing any field collapse due to lightning discharge. Measurements following discharge can supply two types of information. The first type is described by equation 2.4.4:
\[ \Delta V = (5.48 \times 10^{-5}) \Delta E \cos \theta \]

or
\[ \Delta E = (1.8 \times 10^4) \frac{\Delta V}{\cos \theta} \]

This indicates that if the electric field direction is known, then the change in field strength is directly measured as a change in output voltage. This measurement is made by both sensors.

These measurements are particularly useful for determining the percentage of the charge region neutralized by a given lightning event. The neutralization ratios can be compared with ground based field change measurements to determine whether intervening space charge or screening layers affect normal ground based field change measurements.

It is becoming increasingly accepted that ground based electric field measurements do not truly represent thunderstorm electric fields, yet the accuracy of ground based field change measurements is untested. Most estimates of charge neutralized during a lightning event are made from field change measurements using the following equation (Uman, 1969):

\[ \Delta E = \left( \frac{1}{4 \pi \varepsilon_0} \right) \frac{2 \Delta Q \cdot H}{(H^2 + D^2)^{3/2}} \]

or
\[ \Delta Q = (2 \pi \varepsilon_0) \frac{\Delta E (H^2 + D^2)^{3/2}}{H} \]

where
\[ \Delta E = \text{The electric field change} \]
\[ H = \text{Height of the neutralized charge center} \]
\[ D = \text{Horizontal distance from the point of measurement to the ground projection of the neutralized charge region} \]

This equation assumes a point charge region and compensates for an image charge due to the conducting earth. If ground base field change measurements
are inaccurate, then the accepted values for typical charge transfers may need revision. At this point we do not have enough accurate charge center locations from lightning reconstructions to test the validity of equation 3.4.2. In addition, because Langmuir Lab is located on a mountain, the ground based electric field measurements must be corrected for the mountain's form factor. This consideration may require that a definitive test be made with flat ground measurements.

Winn and Byerley (1975), using horizontal electric field data measured with a balloon borne electric field mill, estimated the total charge concentrated in a thundercloud charge region from two lightning events. They first calculated the total charge neutralized using equation 3.4.2. At the same time, they measured the horizontal electric field just prior to and just following the events. They then assumed that the ratio of these fields was proportional to the net charge contained in the region before and after the discharge. Once they knew the ratio of the charges and the total charge neutralized, they could calculate the total charge prior to each event. They estimated that the quantity of charge before each flash was -120 and -160 coulombs.

We used the same technique to estimate the total charge present prior to two flashes. Only two events were analyzed because at this time these were the only discharges of which we have some knowledge on the location of the charge center. Location was determined using acoustic reconstruction techniques (Few, 1975). The quantity of charge calculated from these two
flashes was -100 coul and -150 coul. The average was -130 coul. We must recognize the possibility of errors whenever the balloon is in the proximity of charge regions or whenever more than one charge region exists.

The second type of data that can be determined from lightning flashes is information on the electric field polar angle, theta. If one takes the ratio of horizontal voltage change to vertical voltage change, then, using equations 3.2.6, 3.3.1 and 3.3.2, we get,

\[
\frac{\Delta V_H}{\Delta V_V} = \frac{K (\Delta E) \cos \theta_H}{K (\Delta E) \cos \theta_V} = \frac{\cos \theta_H}{\cos \theta_V}
\]

To a first approximation,

\[
\cos \theta_H = \cos \phi \sin \theta \cos \alpha + \cos \theta \sin \alpha \cos \beta \\
\approx \cos \phi \sin \theta
\]

and

\[
\cos \theta_V \approx \cos (\theta + \alpha \cos \phi + \beta \sin \phi) \approx \cos \theta
\]

since \( \theta \gg \alpha, \beta \) in general

Then

\[
\frac{\Delta V_H}{\Delta V_V} = \frac{\cos \phi \sin \theta}{\cos \theta}
\]

3.4.3

And

\[
\theta \approx \tan^{-1} \left( \frac{\Delta V_H}{\cos \phi \Delta V_V} \right)
\]

Again, caution must be used to insure that the balloon is not in a charge region and that multiple charge regions are not affecting the measurements. These problems are somewhat detectible since multiple charge regions can cause large changes in the electric field azimuth angle following lightning discharges and the balloon profile measurements supply information on the location of
persistent charge regions.

A number of electric field polar angles were calculated using equation 3.4.3. In general, these angles agreed with angles determined using the curve fit technique, and they supplied valuable supplementary information, especially during periods of low balloon wobble.

3.5 Space Charge/Rain Current Analysis

As shown in Section 5 of Chapter II, the BEFS acts as a contact current meter when passing through a region of charged rain. The equations governing this mode are 2.4.2 and 2.4.3.

\[ V_\rho = (9.1 \times 10^6) \omega_\rho \]

\[ V_J = (9.1 \times 10^6) J_R \]

It is relatively easy to remove the effects of other measurement modes from contact current data. One only needs to integrate the data over a time long compared to the spin period. This tends to remove all a.c. components. Figure 21 shows the contact current flowing through the vertical lunes as a function of time during the flight. This data was plotted as if the cause were rain current. The vertical balloon velocity is also shown.

While there is no difficulty in reducing contact current data, the analysis of this data is nebulous. This is because the coupling of the vertical lunes does not permit us to discriminate between charge flowing in the top lune
or out the bottom lune. One cannot uniquely determine whether the balloon is charging or discharging, if either. Chapter IV contains an analysis of the data displayed in Figure 20.

Contact currents can also produce errors in the horizontal curve fit program. As the balloon rotates about its Y axis, the horizontal lunes can receive a net exposure to any vertical contact current. Such an exposure would cause current flow through the horizontal lunes which would have the same appearance as induced charge flow due to balloon wobble and could cause errors in determining theta. This error current can be subtracted from the horizontal output by using the following equation.

\[ \varepsilon = \frac{2 \sqrt{2} \sin \alpha J_R}{C_F} \]

where \( \varepsilon \) = error voltage

Once this factor is removed, accurate determinations of theta are again possible.

### 3.6 Auxiliary Data Analysis

#### 3.6.1 Orientation Sensors

Both the magnetometers and inclinometers were calibrated prior to launch. Balloon azimuth was determined to better than \( \pm 5 \) degrees during most of the flight. Only during times of high turbulence was this accuracy degraded. Balloon inclination was probably accurate to \( \pm 0.5 \) degrees with a resolution of \( \pm 0.1 \) degrees.
Errors could be produced by relative motion between the balloon and the electronics package. The inclinometers measure the motion of the electronics package. We assume that the positive 40 mbar pressure maintained inside the balloon, which produces a stress of 8,000 psi on the balloon surface, insures rigid motion between the electronics package and the balloon. We cannot test this assumption at the ground because of the danger of rupturing the balloon. If the electronics package flexes relative to the balloon, our determinations of balloon inclinations are in error.

3.6.2 Altitude Determination

The pressure gauge, which is calibrated in the lab, is used to determine balloon altitude and vertical velocity. Altitude can be determined from the pressure gauge output voltage using either an altitude/pressure plot based on the U.S. standard atmosphere (1956) or the hydrostatic equation. Since the altitude at balloon launch is known, the initial relationship between altitude and voltage is established. Subsequent altitudes are determined from:

\[ Z = H \ln \frac{V_o}{V_p} \]  \hspace{1cm} 3.6.1

where \( H = \text{Scale height} = \text{mg/kt} \)
\( V_o = \text{Initialized voltage} \)
\( V_p = \text{Gauge output voltage} \)

Balloon altitudes calculated with equation 3.6.1 were in good agreement with altitudes determined by tracking radar.
3.6.3 Temperature Measurements

Temperature measurements by the external thermistor, which is mounted at the bottom surface of the balloon, possibly returned errors as large as 4 degrees (Figure 22). These errors were probably due to the long time constants of the thermistors and to the poor air circulation at the bottom of the balloon. Care has been taken to minimize thermistor self-heating. It is now evident that faster reacting thermistors must be used on future flights.
CHAPTER IV

The Electric Field Measurements

4.1 Background

The BEFS was launched into a thunderstorm over Langmuir Laboratory, New Mexico on 12 August 1975. This particular storm was an excellent example of intense local convective storms generated by the thermal uplifting of moist air over the Magdalena Mountains. The storm travelled slowly in a generally southerly direction at about five km per hour. First nearby lightning occurred at approximately 11:22 MST (Mountain Standard Time). The electric field at the ground reversed and went strongly positive, indicating negative charge overhead, around the same time. Electrical activity then rapidly intensified with lightning averaging one discharge every 20 seconds over the life of the storm. Precipitation at the ground was also intense. Hail completely covered the ground after the storm. The temperature at the ground dropped over 10° C during the storm.

At 11:29:50 MST Winn and Byerley from the New Mexico Institute of Mining and Technology launched their balloon borne electric field meter. This instrument measured horizontal and vertical electric field strength as it rose and descended through the cloud. Their flight duration was forty minutes.
At 11:32:40 MST the BEFS was released. Rising at approximately five meters per second, the balloon reached its maximum altitude of 7.3 km msl (mean sea level) at 11:52 (Figure 10). This apogee was well under the predicted maximum of 8.5 km. Introduction of air during the inflation process and the subsequent loss of free lift account for the reduced ceiling. Prior to launch the BEFS free lift at the balloon hangar was only 6.5 pounds instead of the 15 pounds that had been anticipated. The balloon hangar elevation is 3,223 meters msl.

As already mentioned, the balloon was tracked by radar during its entire flight. Independent tracking was also provided by the combination of GMD-I tracking receiver and the on-board pressure gauge. Results from radar tracking are shown in Figures 10 through 13. These plots show the balloon altitude as a function of time and the X, Y, Z coordinates of the balloon with respect to Langmuir during the entire flight. From these plots we see that the total flight duration was approximately forty-five minutes and that the storm was relatively stationary during the flight. Figure 11 shows that like any well-trained balloon, the BEFS attempted to return to its launch site, but, alas, fell short. The temperature profile, as measured by the on-board thermistor, is shown in Figure 21.

The physical and electrical properties of this storm were well documented. Cameras from distant locations photographed the storm's movement and its physical development. Wind direction and magnitude were
measured at a number of locations. Arrays of rain buckets on the ground recorded the distribution of precipitation. The electric field and electric field changes were measured at a number of ground installations. A high speed vertical scanning radar mapped the reflectivity regions of the cloud. The Rice acoustic array system was installed near the launch site, and it recorded thunder from numerous discharges while the BEFS was in the air.

Data from all these auxiliary sensors has not yet been fully analyzed nor is it all available at this time. The next major effort, now that the electric field analysis is well under way, will be to more completely correlate the BEFS measurements with the ground based data.

4.2 The Field Profile

Figure 14 shows the horizontal field strength, measured by the BEFS, versus time as the balloon ascended through the cloud. Only the ascent profile is plotted because this represents the most accurate data. During descent the balloon collapses and this causes a distortion in the form factor. In addition, because there is no longer a stress on the balloon surface, relative motion between the balloon and the electronics package is more likely. As discussed previously, such relative motion would cause errors in the determination of the inclination of the electric field vector.

Several temperature and altitude values are shown in Figure 14. These points help one visualize any temperature or altitude dependence of the
electric field. Figure 10 gives balloon altitude versus time for more detailed comparisons. As a quick reference the zero degree Celsius isotherm inside the cloud occurred at 5.6 km msl. The minus five degree level was reached at 6.55 km and -8 degree level was at 7.11 km. The maximum balloon altitude was 7.3 km, which corresponded to -9 degrees. The temperature lapse rate inside the cloud was approximately -5.3° C/km.

Naturally, the electric field was vertical at launch and we were unable to get accurate values for the field because of the absence of spin modulation. This remained the situation until after 11:34, at which point we started seeing some spin modulation. The horizontal field component became large enough for accurate spin solutions around 11:35. This corresponds to the time that the balloon entered the cloud and may be an indication of a screening layer. That is, a screening layer would tend to decrease the horizontal field strength outside the cloud and produce an accelerated increase in field strength inside the cloud.

The sharp decreases in field strength seen throughout the flight were caused by lightning discharges. A total of 52 lightning events were measured during the ascending portion of the flight. In most cases the field increased rapidly following a lightning flash. Full recovery often occurred within ten to twenty seconds. The field recovery curves were generally linear. There is little evidence of a decrease in the recovery rate as the field increased toward breakdown, especially in the latter portion of the flight where electrical
activity was intense. This is an important observation because polarizations charging mechanisms such as discussed by Sartor (1967) and Levin and Ziv (1974) predict that, following a discharge, the electric field will initially undergo a rapid increase in intensity. They predict that the rate of increase will then slow as the field tends to self limit near breakdown. We see little evidence of this type of behavior except perhaps when the intervals between flashes are long.

Returning to Figure 14, note several interesting features. After entering the cloud the BEFS rose through a rapidly intensifying horizontal field which reached a peak of 16 kv/m at about 11:38. As the balloon continued to rise, the field decreased until it hit an 8 kv/m plateau near the 0\(^\circ\) isotherm. This plateau started at approximately 5.5 km msl. At 6 km altitude the field again increased to 43 kv/m peak at 6.9 km. This altitude corresponded to a temperature of -7\(^\circ\) C. The BEFS then measured a decreasing field with a minimum field of 8 kv/m occurring at 7.1 km or -8\(^\circ\) C. The horizontal field then rose once again and a maximum value of 49 kv/m was measured just before the balloon started its descent.

It is probable that these various broad peaks and valleys in the horizontal electric field strength were caused by the balloon's position relative to a charge center and not by changes of the field strength with time. In other words, we are seeing variations of the field strength as a function of altitude, not as a function of time. The sharp peaks and decays represent time variations of the electric field. The balloon moved very little during these events.
The dotted lines at the beginning of the flight and between 11:48 to 11:49 represent regions of very poor field determination. The latter problem was caused by slow balloon spin. Large correction factors were needed to compensate for the slow spin and errors are consequently produced. Lack of the horizontal structure needed for spin modulation caused the problems with the early portion of the flight.

It is difficult to draw any conclusions on the height of the negative charge center from the horizontal field data. The decrease in field strength after 11:38 is suggestive that a charge center may have been encountered around 11:42 or at 5.8 km, but nothing is obvious.

Let us digress for a moment and discuss the field structure one would expect to encounter as he approached a charge center. Figure 22 shows the variation in field strength versus height for the on axis profile between two charge regions. The important point is that the field goes to zero at the center of each charge region and that the maximum field is encountered between the regions. For a monopole situation, maximum field would be encountered just as the balloon entered the charge region. If the profile was off axis, the field would be totally horizontal at the altitude of the charge center. In other words, the clues of determining the height of the charge center from electric field profile data are:
a) The height where the vertical component of the field goes to zero and reverses.

b) The positions and shape of the field maximums.

c) The position where the field becomes completely horizontal.

Let us now consider Figures 15 and 16. Figure 15 is a plot of total electric field strength as a function of time during flight. Again altitude and temperature information is included. We see basically the same structure indicated by the horizontal field profile. There is a field strength peak of approximately 38 kv/m centered about 11:37:30 or 5.05 km msl. A relative minimum of 22 kv/m was measured at approximately 11:42 or 5.8 km altitude. The field then increased again, reaching the largest measured value just after 11:50. The relatively large magnitude (69 kv/m) and sharpness of this peak indicates that it may have been produced by time changes in the electric field and not by motion of the balloon relative to the charge centers. The peak of the "envelope" is probably about 45 kv/m. Because the balloon commenced its descent at 11:51:40, we suspect that it did not attain sufficient altitude to accurately determine the last geometric peak.

The obvious differences between the horizontal field profile and the total field profile are size and sharpness of the first major peak as indicated by the total field measurement and the indication of three major peaks in the horizontal field versus only two in the total field. These differences might be explained if the first peak was caused by increases in the horizontal and the vertical components of the field and if the latter peaks were mainly produced
by changes in the horizontal field component only.

Again there is no obvious information on the location of the negative charge center. The 11:38 peak is suggestive, but certainly inconclusive.

Figure 16 shows the variation of the electric field vector's inclination from the vertical as a function of time during the flight. Altitude and temperature are plotted for reference points. This Figure contains very important information. We see that the electric field polar angle is small immediately after launch. A zero degree polar angle means that the electric field vector is totally vertical and upward pointing. This implies that there is negative charge above the balloon. A 180° polar angle would imply a negative vertical field with positive charge above the balloon (or negative below).

After launch, the electric field polar angle slowly increased as the balloon rose. At approximately 11:37, theta increased, then decreased. This bump exactly coincides with the first field strength peak noted in Figures 14 and 15. After the bump, theta again increased very rapidly and passed through ninety degrees at 11:45:10. The altitude where theta equalled 90° should be an indication of the height of the center of the negative charge region.

If we make the 90° point as the determination factor, this would place the negative charge center at 6.72 km msl or -6° C. Further, if we assume that the points where the rate of change of theta changes sharply define the vertical boundaries of the charge region, then we can at least address the
charge center width. The first break point starts just before 11:44 or at 6.3 km. The second point, although not sharp, seems to start around 7.15 km. This would set the charge region width at about 800 km.

Figure 18 shows a smoothed plot of the vertical field versus time. The same field data versus altitude is shown in Figure 19. The effects of lightning discharges have been removed so that the field as a function of altitude can be seen more clearly. Again we see the first peak centered at 11:38 (5.1 km). Following this peak, the vertical field then remained relatively constant until 11:44 at which point the field decreased to zero. After 11:46 the vertical component of the field again intensified but now it was directed downward.

The shape of the vertical profile again suggests that the charge center was located at an altitude of about 6.7 km.

The 11:38 peak does not seem to fit with the rest of the profile. It is possible that this peak was produced by real change in the electric field and not by the motion of the balloon with respect to the thundercloud charge. This question is discussed in the next Section. Another possibility is that the plateau was an anomalous effect and that the peak was due to the thundercloud charge distribution. Even if this was the case it would not change the location of the charge center. The vertical field would have decreased to zero at approximately the same altitude as was actually measured.
The final component of the electric field vector measured during the BEFS' ascent is shown in Figure 17. Phi, which is measured from magnetic north, defines the direction that the horizontal component of the electric field vector is pointing at a given time. Phi is defined in the physical sense, that is the field vector points from positive to negative charge.

We were able to accurately determine the electric field azimuth angle after about 11:35. From 11:35 to 11:37, the azimuth angle rotated slowly from 280 degrees to 315 degrees as the balloon moved in a southeasterly direction at 12 km/hr. From 11:37 to 11:38 the balloon moved almost due south at only 4 km/hr. The azimuth angle remained constant during this minute and resumed its slow rotation toward north as the balloon continued in a generally southeasterly flow during its ascent. The period where the balloon motion slowed and changed direction corresponds to the time of the electric field peak.

The X-Y coordinates of the charge center cannot be determined from change in azimuth angle as a function of horizontal balloon motion. This is because both the balloon and the charge center tend to move with the general motion of the storm. What is revealed in Figure 17 is the seemingly long persistence of the charge center to a certain region of the cloud. The azimuth angle between the charge center and the balloon changed only gradually, except for short term effects due to lightning, during the balloon ascent. Once the balloon neared float, phi changed rapidly to the west, following a lightning
flash, and the balloon’s horizontal motion increased to 45 km/hr.

It is possible that a single center produced the dominant fields measured by the BEFS from launch until 11:48:40, at which time it was destroyed by a very large discharge. It seems that this charge center maintained a surprisingly constant position within the cloud despite numerous lightning discharges. During this period ground observers reported thunder arrivals from the east, west and overhead. Lightning channel locations from thunder reconstructions should prove very interesting during this period of the storm.

4.3 The Anomalous Peak

There is evidence that the 11:37 electric field peak was associated with the storm dynamics. Figure 20 shows possible rain current density measurements and balloon vertical velocity as a function of time. Note that the balloon was in a strong downdraft from approximately 11:36 to 11:38 and a weaker downdraft until approximately 11:43. The first time period coincides with the field peak. Assuming that there was a causal relationship, there are numerous possible interpretations. For instance, negative charge may have been carried down by the downdraft or, possibly, there was increased generation of charge associated with the downdraft.

A popular cloud electrification theory is that charge is generated and separated by falling precipitation (Mason, 1973). With this mechanism charge is
transferred during collisions between falling ice particles and smaller cloud particles in the presence of electric fields. The relative velocity between the particles then serves to separate charge and, consequently, intensifies the electric field.

A major reason for the popularity of the precipitation charging theory are observations that large precipitation shafts often arrive at the ground several minutes after lightning events. These observations have been interpreted to imply that the precipitation produced the lightning. The difficulties with this theory are:

(1) The need for very high precipitation intensities. Rates of 80 to 100 mm/hr seem to be required to produce breakdown field intensities of around 500 kv/m (Mason, 1971, Paluch and Sartor, 1973).

(2) The observation that lightning events often occur prior to any precipitation (Moore, 1974).

(3) Observations that lightning may occur in low radar reflectivity regions (Few, 1974). Low radar reflectivity implies small cloud droplets. Precipitation size particles are highly reflective.

(4) Recent observations that lightning enhances precipitation rather than results from it (Moore, et al, 1964, Few, 1974).

From the BEFS we observed around a 50 per cent increase in the electric field intensity during the downdraft period. We also observed two large and one small field discharges. Preliminary analysis of thunder data indicates that the lightning may have occurred several kilometers on either side of the
balloon. Resolution of whether lightning occurred near the balloon awaits further analysis.

Cloud radar data indicates that the balloon rose through regions of very low reflectivity up to at least 11:44 MST. Obviously the balloon did not experience a precipitation driven downdraft and precipitation charging probably did not occur during the field strength peak.

In fact, there is strong evidence that the 11:42 plateau region of the vertical profile was more affected by falling precipitation than was the 11:37 peak. The Rice precipitation momentum meter indicated a rapid increase in precipitation around 11:43. A large amount of hail fell at that time. The very heavy precipitation lasted for six minutes. During the same time period, a ground based electric field meter indicated a reversal in the field direction. C. B. Moore calls this sequence of events a "GEAWP" (Gradient Excursion Associated With Precipitation). He claims that it is related to, but not caused by, negatively charged precipitation falling to earth. (Private communication).

If one interprets these observations as caused by negatively charged precipitation falling from the negative charge region, then one would expect the precipitation to decrease the electrical energy of the storm and, consequently, the electric field strength. A decrease in the electric field was measured by the balloon, but we have no idea from what region of the cloud the precipitation started. Further, falling negative charge would not cause the measured reversal in the sign of the electric field at the ground. Consequently, we chose not to
propose a specific mechanism to account for our observations, rather we simply
suggest that some of the structure we saw in our electric field measurements
may have been caused by storm dynamics.

4.4 Contact Current Measurements

As discussed in Chapter III, the BEFS measured a low frequency
current as it rose through the cloud. Three possible interpretations of these
measurements were proposed. It was shown that the outputs could have been
produced by rain currents, net space charge on drops or true conduction
currents. Also mentioned in Chapter III was the fact that the differential
coupling of the vertical sensors makes it impossible to discern whether a
positive contact current was produced by positive charge hitting the top of the
balloon or negative charge leaving the bottom. This ambiguity requires that all
interpretations of contact current data be made with great caution.

Rain current is caused by charged hydrometeors moving under the
influence of storm dynamics and gravity. The governing equation for
determining rain current density with our instrument was shown in Section
2.4.3 to be

$$J_R = 110 \ < V_y > \ \ [\text{na/m}^2]$$

where smoothed values of $V_y$ are used.
The dashed line in Figure 20 shows the rain current density as a function of time, calculated from the BEFS contact current measurements with the assumption that all the contact current was produced by the motion of charged drops. With this assumption, we see that the largest rain current density was -70 na/m². The negative sign implies positive charge falling or negative charge rising.

Rain charge density can be deduced from contact current flow between the vertical lunes as the BEFS rises or descends through regions of net charge. In this case the balloon's motion relative to the drops drives the current. (In the rain current interpretation, it is assumed that the motion of charged droplets, and not the balloon, produces the current flow.) The governing equation for the charge density measurement mode was shown in Section 2.4.3 to be

\[ \rho = 110 \frac{<V_V>}{W} \quad [\text{ncoul/m}^3] \]

where \( W \) = vertical velocity of balloon.

Finally, we calculated the total conductivity inside the cloud that would be necessary to produce the observed contact currents. In these calculations it was assumed that all the contact current was produced by charge moving under the influence of the thundercloud electric field. Only the vertical component of the field was considered.
If $J_C$ is the conductivity current density, then,

$$J_C = \lambda E$$

where $\lambda$ = scalar conductivity.

Then the vertical output voltage is given by:

$$V_C = 8 R_F A \bar{J}_C = 8 R_F A \left( \sigma E \right)$$

where $R_F$ = feedback resistor

$A$ = cross sectional area of a lune

and $\lambda = (1.1 \times 10^{-7}) \frac{V_C}{E}$ [m$^{-1}$m$^{-1}$]

There has been much discussion on the magnitude of the electrical conductivity of the air within clouds. The consensus is that, due to rapid attachment of ions to cloud droplets by conduction, migration and ion diffusion, the conductivity of the air should be reduced inside clouds (Phillips, 1967). Freier (1962), however, argued that the rapid recovery period following a lightning discharge requires a high conductivity in the charging regions of thundercloud. He based his calculations on the assumption that the thundercloud charge generation mechanism produces a constant current flow within the cloud. Evans (1969) interpreted his thunderstorm data as indicating that the conductivity inside thunderclouds was a factor of 10 larger than in the air outside the cloud. The accuracy of his measuring method has been strongly questioned (Vonnegut, 1969). Rusk and Moore (1974) measured the conductivity within the bases of electrified thunderclouds and found it to be an order of
magnitude smaller than the conductivity of the clear air just outside the cloud.

Conductivity of the clear air at 6 km altitude is approximately $6 \times 10^{-13} \ \Omega^{-1} \ m^{-1}$. This implies that the conductivity within the cloud should have been less than $10^{-13} \ \Omega^{-1} \ m^{-1}$ throughout the flight. Our calculations indicate that the conductivity that would have been required to produce the measured contact currents was generally on the order of $10^{-12} \ \Omega^{-1} \ m^{-1}$. Further, on three occasions a negative conductivity would have been required to match the data. These facts strongly suggest that true conduction currents did not play a significant part in the measured contact currents.

It is difficult to determine when balloon motion or rain motion produced the greater contact current. In all probability the measured contact current was produced by both motions. The solid line in Figure 21 indicates the balloon vertical velocity during the flight. In comparing this with the dashed line, one notes some indications of couplings between balloon vertical motion and contact current. This coupling, which is more evident in the latter portion of the flight, is apparently weak and out of phase.

The rain current interpretation of the data implies that the rain was negatively charged below the negative charge region. This is just opposite to what is required to charge the cloud via a precipitation powered mechanism. That is, negatively charged rain falling in that region of the cloud would tend to decrease the electrical energy of the storm rather than increase it.
At approximately 11:44 the sign of the rain current suddenly reversed and went strongly negative indicating positively charged precipitation. The maximum rain current we measured was -70 ncoul/m² which implies that the drop size particles carried a space charge density on the order of \( +10^{-8} \) coul/m³.

This reversal in the sign of the rain current occurred approximately one minute before the sign of the vertical electric field reversed. We have insufficient data to discern whether there was a causal relationship between these events, but one tends to be suspicious. It could be that we experienced a case of polarization charging between the balloon and the hydrometeors. The sequence is not quite right in that the rain current changed sign before the field, but it is still a possibility.

Another possibility is that the changes in rain current density were associated with cloud conditions rather than with balloon altitude. Figures 23, 24 and 25 show digital radar cross-sections of the thundercloud at 11:43:19, 11:48:22 and 11:50:40 respectively. Increasing letters indicate decreasing reflectivity. "A" represents maximum cloud reflectivity \( (5 \times 10^{-5} \text{Z}) \) and "Z" represents minimum reflectivity \( (0.0156 \text{Z}) \).

The circle in each radar picture represents the location of the balloon in the cloud at the time of the radar scan. Note that in the 11:43 scan (Figure 23), the balloon was in a region of the cloud with a radar reflectivity of only 2Z. This corresponds to an equivalent rain fall rate of 0.06 mm/hr. (Batten, 1959).
At this point, the BEFS measured positive rain currents. In fact, during the whole ascent up to 11:44, the BEFS was in quite low reflectivity regions of the cloud.

During the 11:48 scan (Figure 24), the cloud reflectivity in the vicinity of the balloon was about 50Z. This corresponds to an equivalent rain fall rate of 0.4 mm/hr. At this point the rain current densities were near zero. By 11:50 (Figure 25), the radar reflectivity in the vicinity of the balloon was greater than 500Z ( 2 mm/hr) and the rain current was strongly negative. This evidence implies a possible correlation between radar reflectivity and rain current density. That is, we measured negative rain currents in regions of high reflectivity and positive currents in low reflectivity regions. It may be that larger cloud particles, which contribute strongly to the radar signal, tend to be positively charged.

An alternative interpretation is that the balloon was in regions of the cloud that contained ice when it indicated strong negative rain currents. This would imply that the ice particles were positively charged.

This discussion has assumed that the contact current measurements were caused by collisions with charged hydrometeors. There is no direct evidence to support this assumption. We need further measurements to test this assumption and to delineate between the possible cause and effect relationships that we described. Hopefully we will eventually fly in conjunction with an instrument that was specifically designed to make rain current measurements.
CHAPTER V

Discussion

5.1 Electric Field Structure

Because the visual portion of lightning below the cloud is essentially vertical and because thunderstorm charge structure has generally been modeled with a vertical dipole, it has long been assumed that lightning is predominately composed of a vertical discharge between the negative charge center and the ground. Only in the past several years have investigators started to discuss the relative importance of the horizontal component of lightning (Teer and Few, 1974, Brantley, et al, 1975). Teer and Few (1974), using their thunder reconstruction technique, showed in an Arizona thunderstorm that the horizontal portion of lightning was generally extended 2 to 4 times longer than the vertical extent. There is no satisfactory theory to explain this apparent predominance of horizontal lightning.

The existence of horizontal electric field structure inside thunderclouds is well established. In a series of over sixty rocket launches, Winn, et al (1974) made short time measurements of the horizontal field intensity. Their horizontal field measurements are generally comparable in magnitude to vertical field measurements made by other investigators (example: Holitza, et al, 1974). They generally measured strong fields but only occasionally did they
measure intense fields ( > $10^5$ v/m). They concluded that regions of very intense fields must be confined to relatively small volumes. Griffiths and Phelps (1976) calculated that electric field strengths of $2.5 \times 10^5$ v/m and greater that extend across a region a few hundred meters in length would be sufficient to initiate the propagation of positive streamers which in turn could enhance the field to breakdown levels.

Our measurements seem to imply that horizontal structure may be as important to the initiation of lightning as vertical field structure. Further, the relatively small fields we measured despite the apparent proximity of the balloon to a charge region supports Winn's contention that the very intense fields are confined to relatively small volumes.

The total vector electric field data as presented in the last chapter supplies information on the location, shape and persistence of the negative charge region. The major characteristics are:

(1) the relatively featureless field structure from cloud base to 6.8 kilometers

(2) the surprisingly constant magnitude of the vertical electric field from the cloud base to 6 kilometers

(3) the relatively small changes in the direction of the horizontal component of the electric field during the balloon ascent

(4) the initially slow variation of the inclination of the electric field from vertical, followed by the very rapid reversal in field direction.
From these features we suggest that:

(1) the location of the charge producing these electric fields remained relatively constant with respect to the balloon location.

(2) the shape of the charge region remained relatively constant.

(3) the charge was not in a simple dipole or spherical like distribution.

(4) the negative charge region had greater horizontal than vertical extent.

From these balloon measurements and from the evidence that horizontal lightning tends to be confined in altitude (Few, 1975), we made a crude charge distribution model of the 12 August 1975 storm. This model was not generated to exactly fit our measurements; obviously there are an infinite number of charge distributions that can be force fitted to a given set of measurements. Our objective with this model was to test how well the field structure produced by a horizontally stratified negative charge layer would fit our measurements versus a standard spherical charge distribution. Only one iteration was made with this model. There was no fine tuning.

The horizontally layered charge model is shown in Figure 26. The rectangularly shaped cloud is 4 km X 4 km X 7.5 km. The cloud base is one kilometer above the ground. A 400 meter thick positively charged screening layer is located at cloud base. It contains a total of 5 coulombs. An 800 meter thick negative charge layer extends from 3.7 to 4.5 km. It contains -100
coulombs. The upper positive charge extends from 4.5 to 8.5 kilometers and contains +100 coulombs. In addition, a 200 meter thick positive space charge layer was added at the ground in order to force the model fields to match the measured fields at the ground.

In order to test this model, we compared the field structure that it would produce with the 12 August 1975 balloon measurements. Calculations were made for variable altitudes with a constant one kilometer horizontal offset from the model cloud center.

Figure 27 compares the inclination of the electric field from vertical for the balloon measurements, the stratified charge model and a dipole charge model. The measured data fits the stratified charge model calculations quite well as the balloon approached and passed through the negative charged region. Calculations for the dipole distribution indicate a much different profile.

Figure 28 compares the vertical field strength for the balloon measurements with calculations for the stratified charge model. Again we see a good fit as the balloon approaches and enters the negative charge region.

Although numerous charge distributions models could be generated, this horizontal stratified model seems to fit the measurements in the vicinity of the negative charge region. In addition, it would quite satisfactorily account for the horizontally layered lightning channels that Teer and Few (1974) have observed. The model centers the negative charge layer at the -9° isotherm
which is in excellent agreement with Few's (1975) lightning reconstruction results.

One must bear in mind that this represents a very crude description of a very complex phenomenon. The storm was mature at the time of balloon release and intensified throughout the ascent. The field and charge structures were probably tremendously complex. This model simply represents the best first order description that we could determine from a single electric field profile.

5.2 Charge Generation

The ultimate goal for a thunderstorm electrification investigation is to determine the charge generation and separation mechanisms that operate within the storm. Once we can accurately describe the electric field structure and charge distribution inside thunderclouds, we can then attempt to understand the physics involved in the electrification process. At this point we can only provide impressions on the relative merits of certain charge generation mechanisms.

In general there are three basic sets of charge generation mechanisms. There is the convection driven mechanism proposed by Vonnegut (1953 and 1963). In these mechanisms, charge is distributed by the convective overturn of cloudy air. The distribution occurs such that a central updraft
portion of the cloud would become positively charged and the outer and lower regions of the cloud would become negatively charged.

Our measurement of the apparent persistence of the negative charge to a particular region of the cloud seems to indicate that the charging mechanism is related to cloud dynamics, as predicted by the convection mechanism. However, measurements indicate that the negative charge region was horizontally stratified. This type of layering is not predicted by the convection theory unless some very stringent thermal stability mechanism is proposed.

Another set of charge generation mechanisms are the many polarization theories (ex. Sartor, 1967; Mason, 1972; Paluch and Sartor, 1973; Levin and Scott, 1975). In these theories charge is transferred during the collisions or near collisions of different size cloud particles moving at relative velocities in the presence of an electric field. Usually updrafts, downdrafts or gravity are used as the separation forces. Our observation of horizontal layering seems to indicate that if the polarization mechanism was important during the BEFS ascent period of the storm, then the polarization mechanism might be temperature dependent. For example, the ice-water induction process treated by Muller-Hillebrand (1954) may be important.

Our measurements of linear recovery curves may be at variance with the induction mechanism, for Kamra (1970) has shown that the rate of charge
separation tends to limit as the electric field strength grows. If this were the case, one would expect that the rate of field grown would decrease as breakdown intensities were approached. This difficulty can be overcome if one assumes that the very intense fields are confined to relatively small regions and that the general field intensities are always much below breakdown levels. Such a situation could occur if the charge generation mechanism operated over a relatively large area and turbulent redistribution of the charged droplets, especially from the cloud boundaries, caused random concentrations of high charge densities.

A third set of charge generation mechanisms involves various interactions of water in the solid phase. There are numerous proposed processes that fit into category. Examples are the drop-splintering mechanism (Latham and Mason, 1961) and the ice crystal-graupel collision process (Reynolds, et al, 1957).

Our measurements of a horizontal charge layer at the -9°C level suggest a temperature dependent charging mechanism. A mechanism involving ice is an obvious possibility. In addition, radar returns indicate that ice or hail may have been present at the charging layer. All this evidence indicates that the charging mechanism may involve water in the ice phase, but certainly no real conclusions can be drawn.
5.3 Future Research

Our next effort will be continued analysis of the 12 August 1975 storm. The vector electric field profile by itself has provided very valuable data, but it supplies very little information on the relationship between field structure and cloud dynamics. By correlating radar, electric field and lightning location data, we hope to uncover any relationships that may exist between cloud reflectivity, charge regions and field structure. Further, we wish to compare this data with the time development of the storm, the general movement of the storm, and the precipitation regions of the storm. In other words, we wish to establish with as much detail as possible the relationships between electrification and cloud morphology.

To gather more data for our electrification research, we will launch a number of improved BEFS into coastal thunderstorms over Kennedy Spacecraft Center during the summer of 1976. These flights will be coordinated with other investigators in conjunction with the Thunderstorm II Project. The aim of this program will be to measure as many parameters as possible during the total life of electrified storms. We will be particularly interested in comparing our electric field and thunder measurements with ground based field and dual doppler radar data, especially during the developing stage of the thunderstorm.

This paper has shown the value gained in measuring the full vector electric field instead of just the scaler field. It also showed that knowing only electric fields and possibly rain current is not enough to adequately describe
cloud electrification. The thunderstorm is too complex for single parameter characterization. Only through experiments rivalling the storm's complexity can man begin to understand the thunderstorm's beauty and possible physical simplicity.
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APPENDIX A

To determine balloon orientation using two inclinometers and two magnetometers, we run a series of four rotations, then run the same rotations a second time after a change of order.

1) Rotation A: About Y-axis (+); (rotation from magnetic field aligned system to gravity/magnetic system)

\[
A = \begin{pmatrix}
\cos \theta' & 0 & \sin \theta' \\
0 & 1 & 0 \\
-\sin \theta' & 0 & \cos \theta'
\end{pmatrix}
\]

2) Rotation B: About Z-axis (+); (change in balloon azimuth)

\[
B = \begin{pmatrix}
\cos \varphi & \sin \varphi & 0 \\
-\sin \varphi & \cos \varphi & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

3) Rotation C: About X-axis (-)

\[
C = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \beta & -\sin \beta \\
0 & \sin \beta & \cos \beta
\end{pmatrix}
\]

4) Rotation D: About Y-axis (-)

\[
D = \begin{pmatrix}
\cos \alpha & 0 & -\sin \alpha \\
0 & 1 & 0 \\
\sin \alpha & 0 & \cos \alpha
\end{pmatrix}
\]
First we calculate

\[ M = DCBA, \text{ then we calculate} \]

\[ M' = CDBA\]

\[
B = \begin{pmatrix}
\cos \varphi \cos \theta \\
-\sin \varphi \cos \theta \\
-\sin \theta
\end{pmatrix}
\begin{pmatrix}
\sin \varphi \\
\cos \varphi \\
0
\end{pmatrix}
\begin{pmatrix}
\cos \varphi \sin \theta
\end{pmatrix}
\]

\[
CBA = \begin{pmatrix}
\cos \varphi \cos \theta \\
-\cos \beta \sin \varphi \cos \theta + \sin \beta \sin \varphi
\end{pmatrix}
\begin{pmatrix}
\sin \varphi \\
\cos \beta \cos \varphi
\end{pmatrix}
\begin{pmatrix}
\cos \varphi \sin \theta
\end{pmatrix}
\]

\[
M = \begin{pmatrix}
\cos \alpha \cos \varphi \cos \theta \\
-\sin \alpha \left( \sin \beta \sin \varphi \cos \theta + \cos \beta \sin \varphi \right)
\end{pmatrix}
\begin{pmatrix}
\cos \alpha \sin \varphi \\
+ \sin \alpha \left( \sin \beta \sin \varphi \cos \theta + \cos \beta \sin \varphi \right)
\end{pmatrix}
\begin{pmatrix}
\cos \varphi \sin \theta
\end{pmatrix}
\]

\[
DBA = \begin{pmatrix}
\cos \alpha \cos \varphi \cos \theta + \sin \alpha \sin \varphi \\
-\sin \varphi \cos \theta \\
\sin \alpha \cos \varphi \cos \theta - \cos \alpha \sin \varphi
\end{pmatrix}
\begin{pmatrix}
\cos \alpha \sin \theta \\
\cos \varphi \\
\sin \alpha \sin \varphi
\end{pmatrix}
\begin{pmatrix}
\cos \varphi \sin \theta
\end{pmatrix}
\]

\[
\begin{pmatrix}
\cos \alpha \cos \varphi \sin \theta \\
-\sin \alpha \cos \varphi \sin \theta - \sin \alpha \cos \varphi
\end{pmatrix}
\begin{pmatrix}
\cos \alpha \sin \varphi \\
-\sin \alpha \cos \theta
\end{pmatrix}
\begin{pmatrix}
\cos \varphi \sin \theta
\end{pmatrix}
\]

\[
\begin{pmatrix}
\cos \alpha \cos \varphi \sin \theta \\
-\sin \alpha \cos \varphi \sin \theta + \sin \alpha \cos \theta
\end{pmatrix}
\begin{pmatrix}
\cos \alpha \sin \theta \\
-\sin \alpha \cos \theta
\end{pmatrix}
\begin{pmatrix}
\cos \varphi \sin \theta
\end{pmatrix}
\]
\[
M' = \begin{pmatrix}
\cos \alpha \cos \phi \cos \theta & \cos \alpha \sin \phi & \cos \alpha \cos \phi \sin \theta \\
+ \sin \alpha \sin \theta & - \sin \alpha \cos \theta \\
- \cos \beta \sin \phi \cos \theta & \cos \beta \cos \phi & - \cos \beta \sin \phi \sin \theta \\
- \sin \beta (\sin \alpha \cos \phi \cos \theta & - \sin \beta \sin \alpha \sin \phi & - \sin \beta (\sin \alpha \cos \phi \sin \theta \\
- \cos \alpha \sin \theta & + \cos \beta \cos \phi \sin \theta & - \cos \beta (\sin \alpha \cos \phi \sin \theta)
\end{pmatrix}
\]

Now, in the original equations, \( X = Y = 0 \) because they are at right angles to the magnetic field lines in the original coordinate system (field aligned). Therefore, the transformed equations reduce to:

CASE 1 (M)

\[
X' / Z = \cos \alpha \cos \phi \sin \theta + \sin \alpha (\sin \beta \sin \phi \sin \theta - \cos \beta \cos \theta) = \cos X
\]

1

\[
Y' / Z = - \cos \beta \sin \phi \sin \theta - \sin \beta \cos \theta = \cos Y
\]

2

\[
Z' / Z = \sin \alpha \cos \phi \sin \theta - \cos \alpha (\sin \beta \sin \phi \sin \theta - \cos \beta \cos \theta) = \cos Z
\]

3

where \( \cos X \), \( \cos Y \), \( \cos Z \) are the direction cosines from the magnetic field vector to the indicated axis (i.e., what the magnetometers measure).

From 2:

\[
\sin \phi = - \frac{\cos \gamma + \sin \beta \cos \theta}{\cos \beta \sin \theta}
\]
CASE 2 (M)

\[ \cos X' = \cos \alpha \cos \varphi \sin \theta - \sin \alpha \cos \theta \]

1'

\[ \cos Y = -\cos \beta \sin \varphi \sin \theta - \sin \beta (\sin \alpha \cos \varphi \sin \theta + \cos \alpha \cos \theta) \]

2'

\[ \cos Z = -\sin \beta \sin \varphi \sin \theta + \cos \beta (\sin \alpha \cos \varphi \sin \theta + \cos \alpha \cos \theta) \]

3'

From 2':

\[ \cos \varphi = \frac{\cos X + \sin \alpha \cos \theta}{\cos \alpha \sin \theta} \]

Hence,

\[ \varphi = \tan^{-1} \left[ \frac{\cos \alpha}{\cos \beta} \cdot \left( \frac{\cos Y - \sin \beta \cos \theta}{\cos X + \sin \alpha \cos \theta} \right) \right] \]
APPENDIX B

As shown in the block diagram of Figure 3, the BEFS electronics package consists of four major sections: the electric field sensors and conditioning electronics; the auxiliary data sensors and their associated electronics; the multiplexer and digital conversion section; and the transmitter section. Section 2.5 gave a brief description of the electronics system. This appendix documents the circuits actually used.

B.1 Charge Amplifier. The voltage output from this amplifier is directly proportional to the charge flowing between sensors as long as the system is in the linear portion of its response curve. See Figure 3 for the frequency response of this amplifier. The equation for the output from this amplifier is

\[ V_o = -\frac{\Delta Q}{C_F} \]

B.2 Compressor Amplifier. This amplifier effectively increases the dynamic range of the electric field meters. If the signal from the front end amplifier is less than ±2 volts, it is amplified by a factor of four. If the signal is greater than ±2 volts, the compressor amp gain factor is one-fourth for that portion of the signal in excess of ±2 volts.

B.3 Auxiliary Data Circuits. Consist of a number of voltage regulators and auxiliary circuits. The regulator component includes two dual-tracking ±15 volt regulators, a +5 volt regulator, and a ±12.5 volt regulator. The auxiliary circuits
include a precision 200 m-amp constant current source, three high gain
magnetometer amplifiers, a l.C. pressure transducer, and two thermistor
circuits.

B.4 Digital Control Board. Includes a crystal clock, a l6 channel analog
multiplexer, counters, and logic gates. This board controls the data flow from
the multiplexer to the sample/hold amplifier and the analog to digital (A/D)
converter. This board also contains the logic that converts the parallel two's
complement output from the A/D converter into either biphase or non-return-
to-zero coding.

B.5 The Digital Conversion Board. Includes a sample/hold amplifier, l2 bit
A/D converter and shift registers. The components on this board convert the
analog data into a pulse-code-modulated digital format.

B.6 The Transmitter Board. Consists of a DC-DC converter, regulator,
frequency modulator, and a 1680 mhz transmitter. The DC-DC converter
increases the battery voltage from 5.6 voits to over 160 voits. This voltage is
then regulated to approximately 90 voits and is fed to the plate of the
transmitter tube. This plate voltage is modulated via the capacitively coupled
PCM data. Modulating the plate voltage causes changes in the transmitter
output frequency. In this manner the PCM encoded data frequency modulates
the transmitter.
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R2


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FIGURE CAPTIONS

Figure 1  Physical configuration of the Balloon Electric Field Sensor

Figure 2  Balloon coordinate system. Direction cosines from lunar centers to E are indicated.

Figure 3  Frequency response of charge amplifier.

Figure 4  Block diagram of the BEFS data acquisition system.

Figure 5  Compressor amplifier transfer function. Output voltage as a function of input voltage is shown.

Figure 6  Location of orientation sensors.

Figure 7  Orientation transformation. The X, Y, Z coordinate system (heavy solid lines) represent the balloon orientation prior to rotations. The primed system (dashed lines) represent balloon orientation after transformation.

Figure 8  Horizontal lune orientation. \( \theta \) is the angle between the center of the horizontal lune and the electric field vector \( E \). \( \alpha \) is the angular rotation about the Y axis as indicated by the Y axis inclinometer.

Figure 9  Vertical lune orientation. \( \theta \) is the angle between the center of the vertical lune and the electric field vector \( E \). \( \alpha \) is the angular rotation about the Y axis and \( \beta \) is the balloon's rotation about the X axis.

Figure 10  Balloon altitude in kilometers above mean sea level versus time in Mountain Standard Time. The arrows indicate the inclination and relative strength of the electric field.
Figure 11: An X-Y plot of the balloon trajectory. The axis origin is centered on Langmuir Laboratory. The arrows indicate the direction and relative strength of the horizontal component of the electric field.

Figure 12: X-Z plot of the balloon trajectory.

Figure 13: Y-Z plot of the balloon trajectory.

Figure 14: The horizontal component of the electric field strength in kilovolts/meter. Time, altitude and temperature are indicated. The sharp decreases in the field are causes by lightning discharges.

Figure 15: Electric field strength versus time, altitude and temperature. The dashed lines indicate periods of poorly determined field strength.

Figure 16: The angle between vertical and the electric field vector as measured at the balloon.

Figure 17: The direction of the horizontal component of the electric field in geomagnetic coordinates. The sharp changes in azimuth were due to lightning discharges.

Figure 18: Vertical component of the electric field in kilovolts per meter versus time. The effects of lightning events on the field are not indicated.

Figure 19: Vertical electric field versus altitude. The field reversed at approximately 6.8 kilometers. Lightning effects are not indicated.

Figure 20: Contact currents (dashed line) and balloon vertical velocity (solid line) versus time is plotted. Positive currents indicate negatively charged hydrometeors. A positive vertical velocity means the balloon is rising.

Figure 21: Air temperature near the balloon versus time during the flight.

Figure 22: Qualitative vertical field profile one would expect from a uniform dipole charge distribution.
Figures 23, 24 and 25

Digital radar scan of the 12 August 1975 thundercloud. The balloon location is circled in each plot. The letters indicate the degree of cloud reflectivity in alphabetical order. That is, "A" represents strongest reflectivity and "Z" represents weakest.

Figure 26

Horizontally layered charge distribution model. Region one extends from 4.5 to 8.5 kilometers in height and contains +100 coulombs. Region two extends from 3.7 to 4.5 kilometers and contains -100 coulombs. Region three extends from 1.0 to 1.4 kilometers and contains +5 coulombs. The horizontal extent of the cloud model is 4 kilometers by 4 kilometers.

Figure 27

Comparison of the electric field inclination calculated for a dipole charge distribution (short dashed line), for the charge distribution indicated in Figure 28 (long dash) with the measurements made during the 12 August 1975 storm (solid lines).

Figure 28

Comparison of the vertical field profile actually measured during the 12 August storm (solid line) with the profile that would be produced by the layered charge model.
COMPRESSOR AMP GAIN

$V_{out}$

$V_{in}$
VERTICAL LUNE ORIENTATION
STRATIFIED-CHARGE CLOUD MODEL