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THE CLOUD EFFECTS PHASE OF THE LASER INDUCED LIGHTNING INVESTIG--ETC(U)
APR 80 C B MOORE, D N HOLDEN, J GRISWOLD AFOSR-78-3722

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AFOSR-TR- 80-0454

Final Report
On The
Cloud Effects Phase
Of The

Laser Induced Lightning Investigation

By
Wright Patterson AFB(AFFDL/FES)

And
Langmuir Laboratory New Mexico Tech

INTRODUCTION:

In June 1978 under Grant AFOSR-78-3722, a cooperative study by personnel from Wright Patterson AFB and New Mexico Tech was begun into the possibilities of triggering lightning from thunderstorms over a mountain top laboratory by use of a high powered laser. The study included investigations of the behavior of the laser and its power supplies at high altitudes and measurements of the atmospheric ionization that were produced. This effort was carried out by the scientists from Wright Patterson AFB (Jack Lippert, Capt. Charles Shubert, and their associates).

The New Mexico Tech portion of the research was aimed at

1. establishment of suitable laboratory facilities on a meadow 2 km North of Langmuir Laboratory near the summit of the Magdalena Mountains in the Cibola National Forest of central New Mexico.
2. with the measurements of the electric fields in the vicinity of the operational site.
3. with the mapping of lightning in the vicinity by acoustic and video systems.

In order that this research could be undertaken in the National Forest, extensive arrangements with the U. S. Forest Service were required. Archeological surveys of the site were made and elaborate safety precautions were established. Laboratory trailers were taken up the Laboratory access road to the 3230 m level and provided with lightning rods and arrestors. A special, metal-sheathed power line was laid from the Comet observatory to the laser trailer complex. Timing signals (IRIG-B) from the Laboratory's time code generator were provided at the complex for coordination of laser operations and studies of lightning location and behavior. A map of the facilities is shown in Figure 1.1.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A mountain-top laboratory facility has been established in central New Mexico for studies of the effects of high powered lasers on the ionization of the air and on the possible triggering of lightning from thunderclouds overhead. A net of electric field meters and another one with television cameras and video recorders have been established for determinations of the nature of normal and of triggered lightning in the operational area.		

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20. Abstract

We have previously observed that electric fields at the surface of the earth are greatly attenuated by the space charges produced by coronae from exposed conductors on the earth. One result of this phenomenon is that the electric field at the earth's surface are limited to an approximate steady state regardless of any intensification aloft and this makes difficult any choice of optimum times for the lightning triggering attempts.

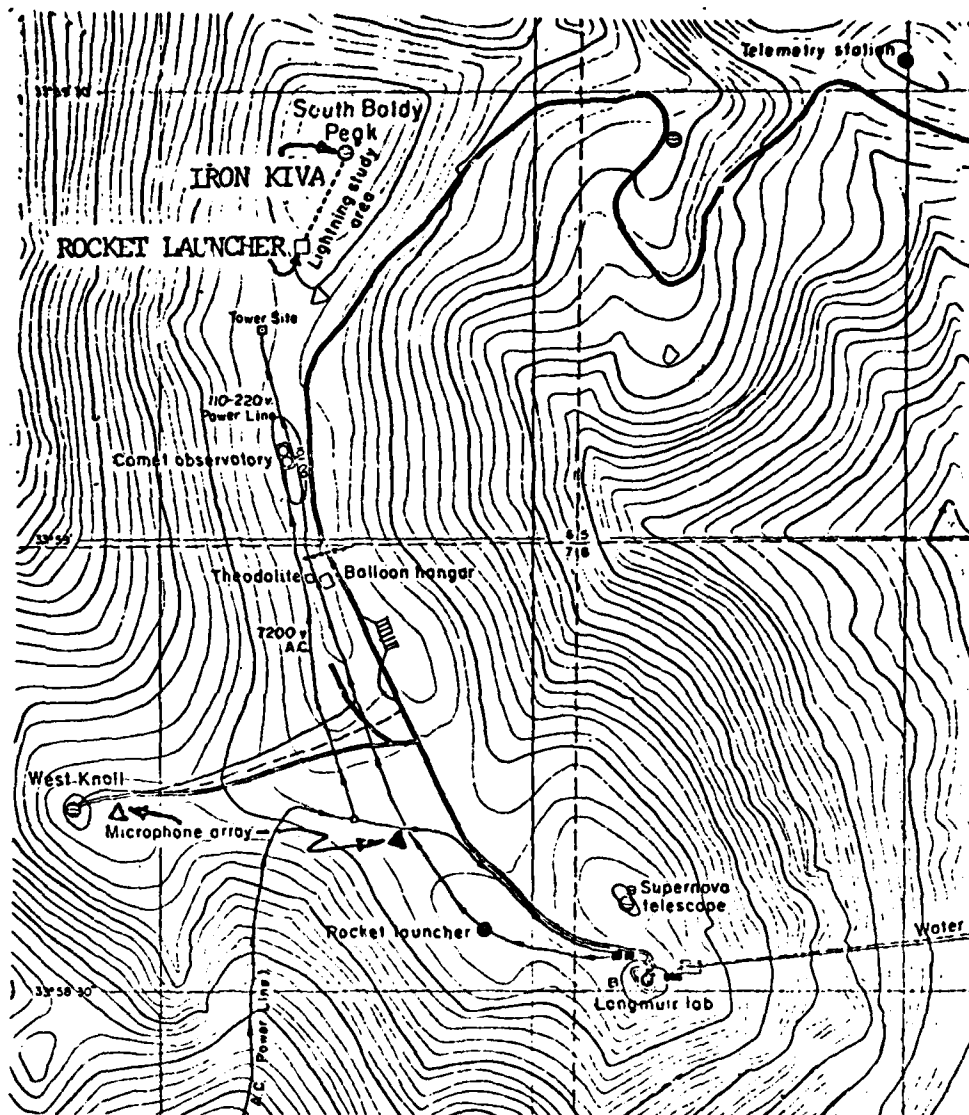
~~In this Air Force study we carried~~ a special electric field meter ^{IS CARRIED} beneath a captive balloon to heights of about 600 m above the facility and measured the electric fields there for the entire life of several storms. The field strengths aloft were as much as 6 fold greater than those observed at the surface; the field changes after lightning did not show the characteristic reversal caused by the corona produced space charge and the field after lightning recovered with a linear increase until lightning occurred again. Monitoring of electric fields aloft therefore provide a better choice of the optimum times for a lightning triggering attempt.

In these studies, some anomalous effects of charge transfers by lightning were also observed repeatedly: lightning appeared to deposit positive charge onto precipitation particles low in a cloud. This positively-charged precipitation subsequently fell out and dominated the electric fields beneath the storm for a radius of about 1 km. The fall of this charged precipitation aided in the cloud's further electrification and usually resulted in the occurrence of another lightning flash.

We believe that the phenomenon known as the "lower positive charge center" may often be caused by the deposition of positive charge on rain by a lightning flash. It also appears that the growth of observed rain may have been aided by electrical effects.

As part of the 1979 field work, lightning discharges were induced twice by the use of wire-trailing, French rockets fired into thunderclouds over the Magdalena Mountains. As a result, interesting measurements of the breakdown process were obtained using AF Weapons Laboratory electromagnetic sensors: Magnetic field derivative signals in excess of 17 Teslas/second were observed in one of the triggered discharges.

Our studies on this technique are continuing.



Iron Kiva altitude: 3275m. m.s.l.
map contour decrements: 13m

Figure 1.1 Top view of electromagnetic and related measurement layout around South Baldy Peak, New Mexico

A

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INSTRUMENTATION:

The apparatus used in these studies of triggered lightning consisted of

1. a net of six electric field mills mounted flush with the earths surface and separated by about 700 to 1000 m in the mountain top meadow that surrounded the site.
2. Three electric field change meters (slow antennas) with 0.5 millisecond resolution for the characterization of lightning strokes in the vicinity. With these the nature of the breakdown processes, the leader streamers, return strokes, dart leaders, continuing currents, K changes and other features of a lightning discharge can be identified and characterized.
3. Two acoustic array, each consisting of three, low-frequency microphones spaced 30 meters apart in an equilateral triangle. These arrays are used to measure the direction cosines for describing the thunder wave-front for each peal of thunder. With knowledge of the direction cosines and the time intervals between the electric field changes caused by the lightning and the arrival of each portion of the thunder, it is possible to map the lightning channels in the clouds overhead. (Few, A. A. (1970), Gutjahr & Holmes (1973), Winn et.al. (1978)).
4. Three video cameras with magnetic recorders and 16 millisecond response (Winn, Aldridge, Moore (1973). Two of these systems were wide angle arrangements that kept the entire sky under surveillance on either side of the laser operations. The third one of these was located at Langmuir Laboratory looking over the laser site. It used a 16mm lens and gave a less distorted view of lightning in its field of view than did the whole sky arrangements. IRIG-B time code with 1 millisecond resolution was recorded on the audio channel of each video recorder for correlation of lightning events with the other data collected for the event.
5. A balloon borne electric field meter carried aloft over the laser site by a plastic captive balloon with a fiber-glass-epoxy tether. (Standler & Winn, 1979) This balloon was used to measure the strength and polarity of the electric field vector aloft above the region of space charge produced by corona discharge processes at the earths surface. This space charge limits the strength of the electric field at the mountain top to values of the order of 10^4Vm^{-1} so that

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INSTRUMENTATION: Continued

the optimum time for firing a laser into a region of strong electric fields is difficult to discern at heights of 500 m or so above the earth. The effects of this charge are much reduced a few hundred meters above the earth so that the fields aloft are often very much stronger than at the surface. The intensification of the clouds electrification leading to a discharge can be monitored directly from a balloon borne instrument.

6. A vertically-scanning, 3 cm wavelength cloud physics radar at Langmuir Laboratory. This radar scanned the hemisphere over the Laboratory once every 132 seconds with 50 vertical scan planes. The data from the radar were gated into 29 range segments each 300 m long in range and one antenna beam width (1.6° , $1/36$ radian) across the beam. Twelve-pulse averages over each beam width were recorded digitally onto magnetic tape and later processed into color-coded displays of cloud echo reflectivity over the Laboratory. (Winn et.al. 1978).
7. A Air Force Weapons Laboratory system for the measurement of dB/dt and dD/dt caused by nearby lightning.

RESULTS: 1978

The principal activities during the 1978 summer thunderstorm season consisted of setting up and equipping the laser site, the making of test firings of the laser with measurements of the ionization produced, and the installation and operation of the lightning monitoring instrumentation. No attempts were made to direct the laser beam into thunderstorms during this season because of Forest Service and operational limitations.

The first simultaneous measurements of thunderstorm electric fields at cloud base level and at the surface of the earth over the entire life of a storm were obtained; an example of these new measurements is shown in Figure 1, 2, and 3. The center of this storm (and the principal rain shaft that fell from it) were about 2 km east of the region where these measurements were taken.

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RESULTS: Continued

Although the two, ground-based field meters were separated by about 1.5 km, they show about the same sequence for the surface electric fields. The captive balloon measurements were made at a height of about 600 m above the earth; these are shown in Figure 3. In this figure, it can be seen that the fields aloft (and to the side of a thundercloud) are several fold stronger than at the earth. Another point of interest is the reversal of the field polarity at the earth's surface after a discharge neutralized negative charge in the lower region of the cloud. This reversal is a superposition effect: The prevalent corona-produced, positive space charge layer just above the earth is essentially unaffected by the flash so that it dominates the surface electric fields temporarily after much of the negative charge in the cloud base had been neutralized by the discharge. This causes a temporary reversal in the polarity of the electric field at the center until the negative charge generator aloft again dominates the clouds external field.

This polarity reversal is not seen by field meter near cloud base: The effect of the lightning here is to reduce the local field strength which regenerates almost linearly after the flash until breakdown occurs again.

The use of a field meter on a captive balloon therefore can permit an improved selection of the time at which a laser should be fired for the triggering of lightning; the chances for triggering will be best when the field strength aloft high.

An interesting phenomenon observed with this instrumentation during the summer was the apparent deposition of positive charge onto precipitation by lightning in the lower portions of several thunderclouds. This positively charged precipitation fell from the cloud base a short time after the discharge and often produced an anomalous electric field over a region 1 km or so in radius around the site of the flash.

As the charged precipitation fell below the level of the captive balloon, the field strengths aloft increased rapidly in strength until they were limited by another lightning flash in the same region as the first one, (See Figure 4-11).

For the three cases that we observed, the deposition of positive charge on precipitation near the cloud base, followed by an electric field anomaly beneath the cloud and terminated by another discharge appears to be a clear case in which the fall of positive charge on precipitation from the cloud base aids the cloud's electrification and causes the second lightning

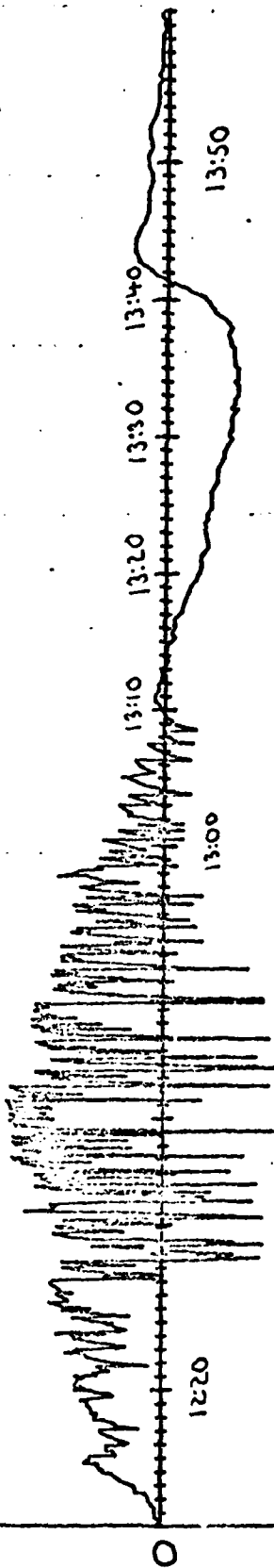
+30KV/M

-30KV/M

782333

LANGMUIR LAB

GROUND E



12:10 MST

Time →

FIGURE 1

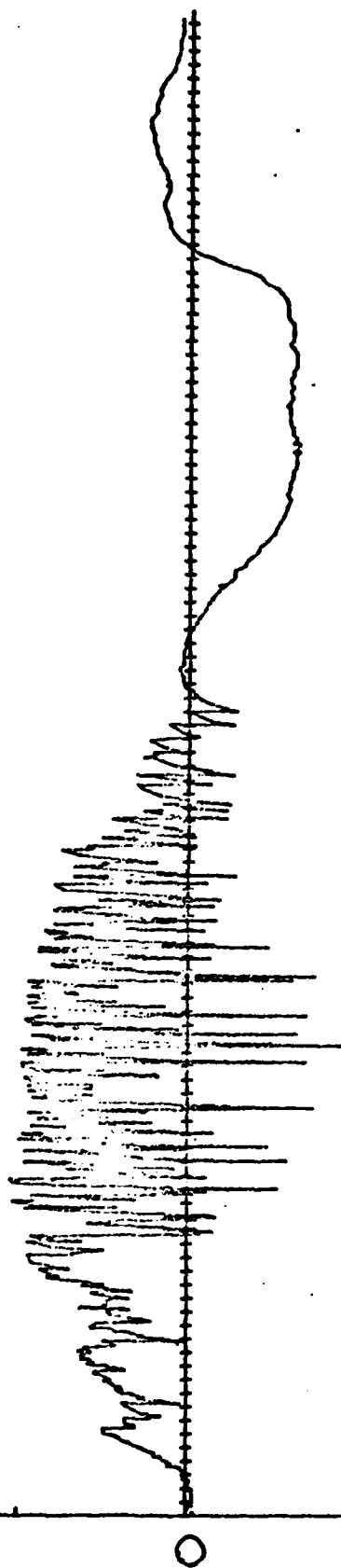
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+30KV/M

78233

SOLAR TOWER

GROUND E



14

-30KV/M

12:10 MST

Figure 2

14:0

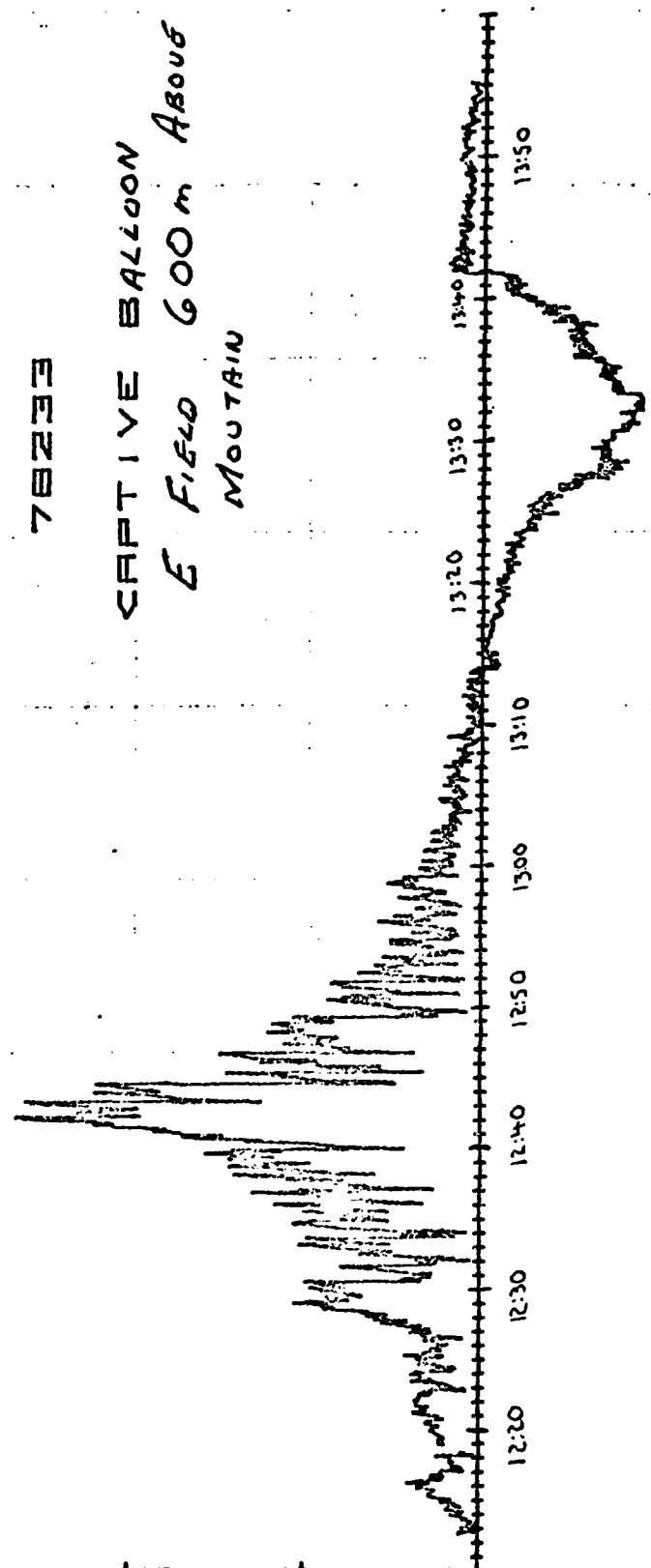
+30KV+

-30KV-

0

17

78233
CAPTIVE BALLOON
E FIELD 600m ABOVE
MOUNTAIN



TIME →

12:10

14:0

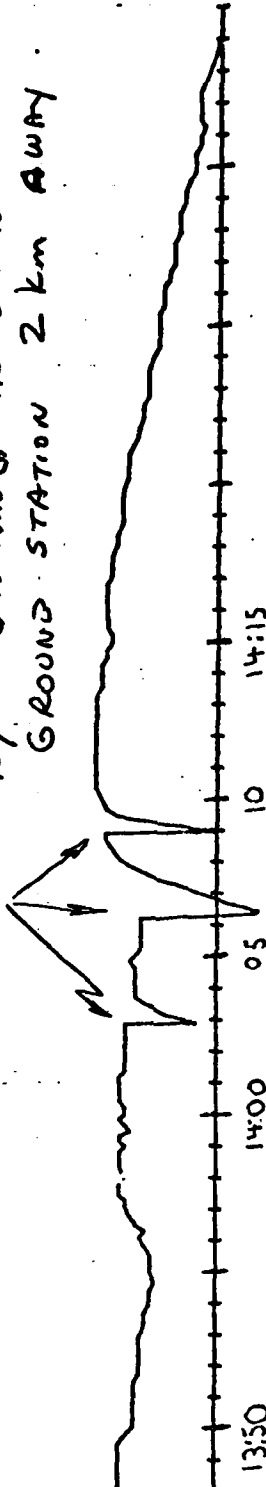
FIGURE 3

+20KV
M

78213

Langmuir Ground Record

E FIELD CHANGES CAUSED
BY LIGHTNING AS SEEN FROM
GROUND STATION 2 km AWAY



0

M

MST →

FIGURE 4

13:44

14:35

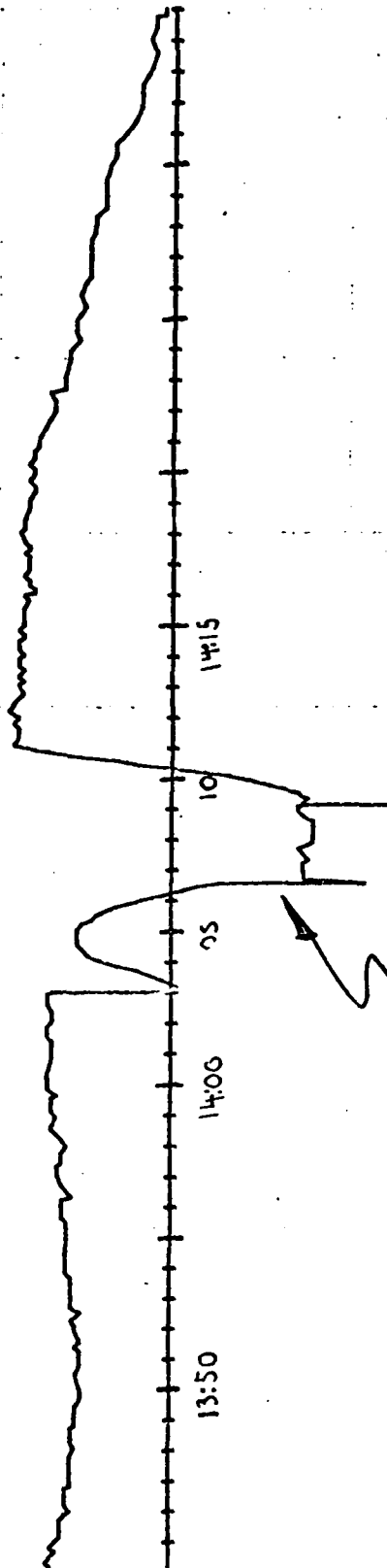
+20KV
m

W, 0

-20KV
m

78213

West Knoll Ground Record



DELAYED EFFECT OF POSITIVE CHARGE
DEPOSITED ON FALLING PRECIPITATION
BY LIGHTNING

M/S →

1435

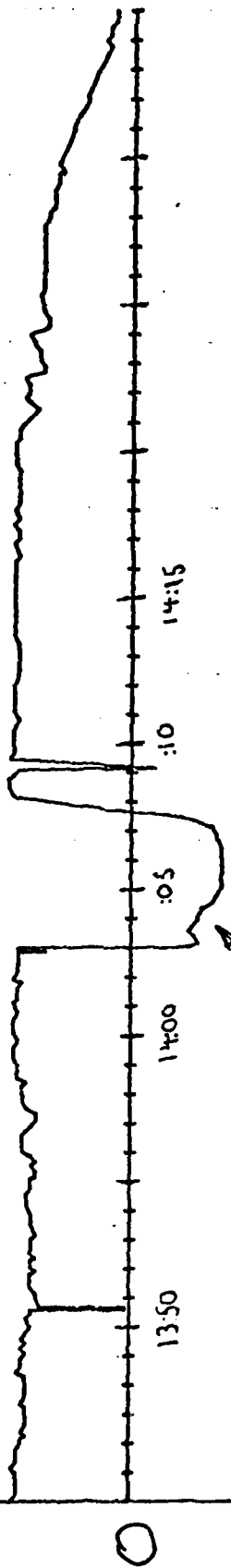
14:35

FIGURE 5

+20KV
M

78213

Solar Tower Grand Rec



ANOMALOUS E FIELD CAUSED BY LIGHTNING'S
DEPOSITION OF POSITIVE CHARGE ON
FALLING PRECIPITATION

MST →

-20KV
M

FIGURE 6

13:44

14:35

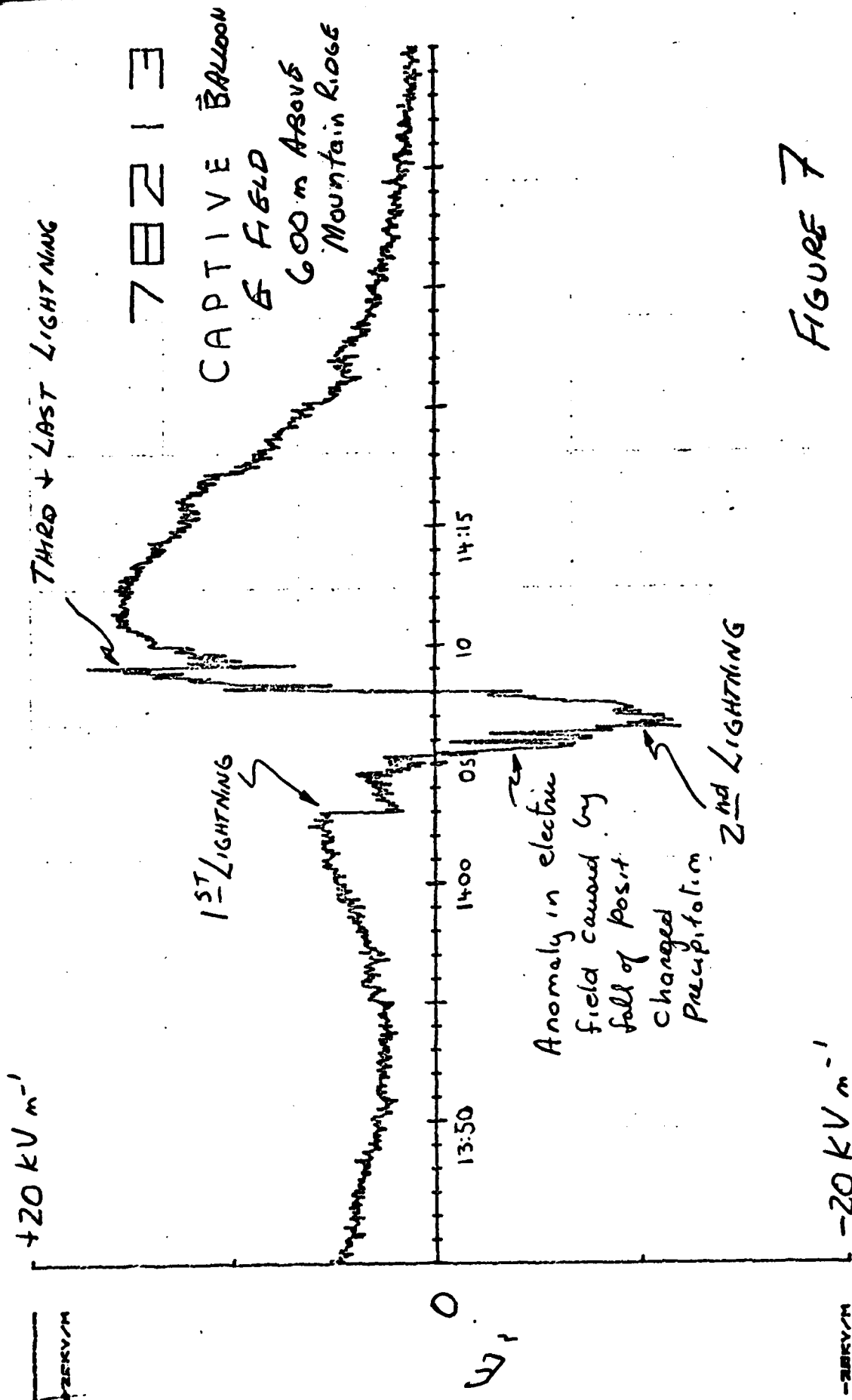


FIGURE 7

13:44 MST EACH TICK ONE MINUTE 14 35

SURFACE FIELD

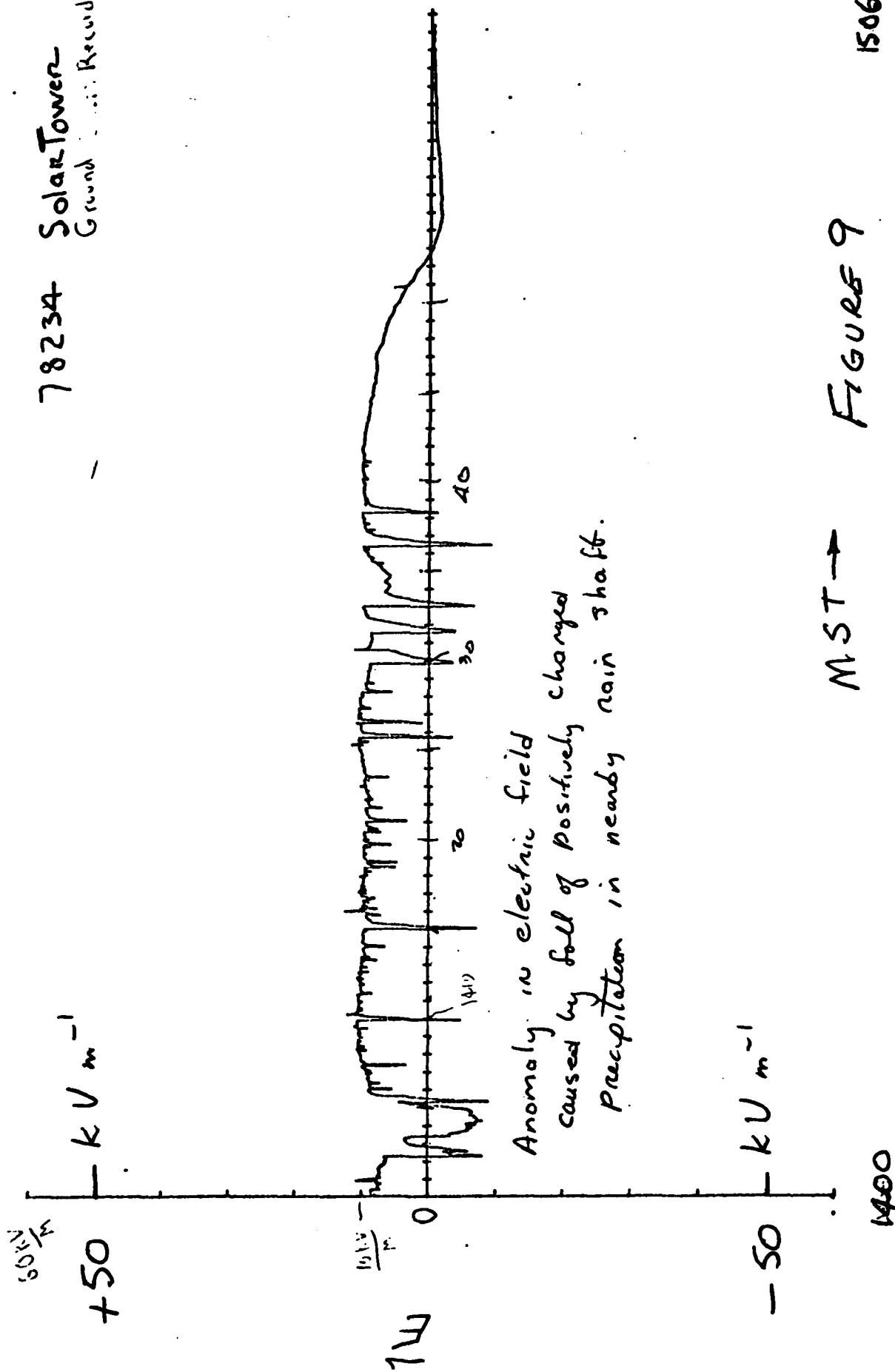


Each Tick = one minute

FIGURE 8

1506

78234 Solar Tower
Ground Record



MST → FIGURE 9

1 Tick = one minute

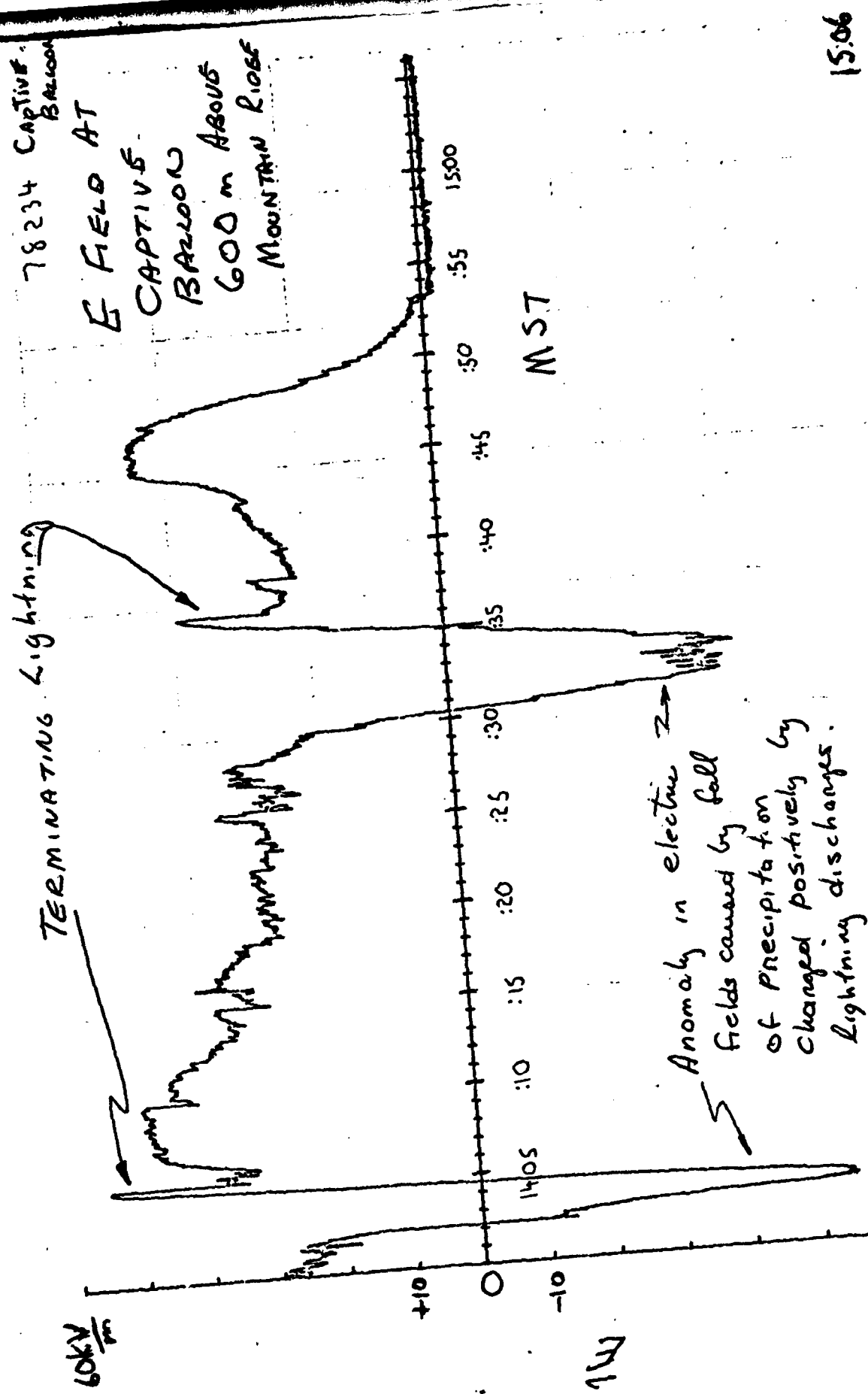
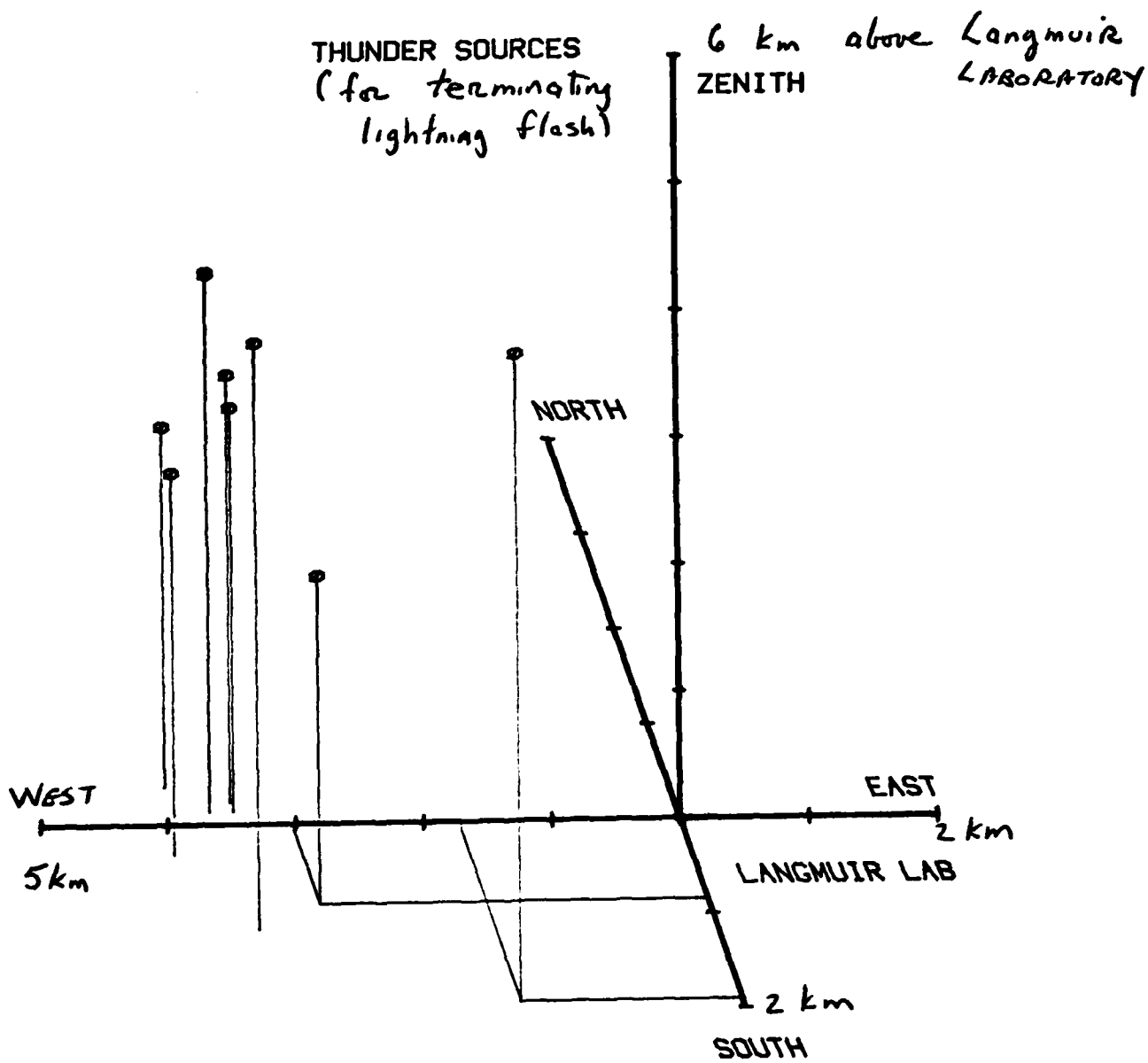


Figure 10

15:06



78234 1436:19.067 M. S. T.

FIGURE 11

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RESULTS: Continued

flash. It is of interest however that this observed sequence has the wrong polarity to be readily explicable by the usual inductive mechanisms suggested for cloud electrification.

The existence of a lower positive charge center in thunderclouds has long been known but its origins have been unknown, Moore et.al. (1959), after observing electric field excursions associated with precipitation with a single field meter and with a single rain gauge, suggested that they may be caused by down drafts that displace the negative charges in the lower regions of a cloud to the side so that an electrical "window" is opened into the cloud top region where a net positive charge is known to exist. There are cases in which positive charges dominate the electric fields beneath shower clouds in the absence of lightning so that this explanation may still have an application.

In the cooperative measurements made during the 1978 summer, it is clear that on occasion, lightning actually deposited a net charge onto precipitation particles and that the subsequent fall of this precipitation tends to aid with the further electrification of the cloud for a short time. There are even some suggestions from the radar data that the lightning may have aided in the sudden growth of the precipitation but we are hesitant to pursue this speculation until more data are available.

A report on these findings was presented at the American Geophysical Union annual meeting in San Francisco, December 3, 1979, as paper M-30. A more complete report that includes the 1979 findings has been accepted for the Sixth International Conference on Atmospheric Electricity in Manchester, England on August, 1980. A copy of the abstract for the Manchester conference is enclosed.

In a parallel effort, Dr. Charles Holmes and his associates have been studying lightning with a 10 cm radar to determine the nature of lightning channels and to observe the effect of the discharge on the cloud particles in the vicinity of the channel. We have obtained more than 150 video recordings of lightning channel echoes and have been able to make some inferences on the channel temperatures and extents. In our earlier work we had some difficulties with the radar preamplifier whose dynamic range was insufficient; it often saturated due to the local precipitation echoes and could only be used to examine the upper regions of thunderclouds. Despite this problem we observed a number of precipitation echoes following lightning and recorded one that clearly developed in the same cloudy volume where lightning had flashed a second or so earlier.

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RESULTS: Continued

It seems to us that the continued laser study should include a 10 cm radar to record the resulting electron concentrations and their effects on electrical discharges from the clouds over the laser site.

To this end, we have obtained a solid state, 30 MHz log IF amplifier with an 80 dB dynamic range for use with the 10 cm radar during the summer 1979 for a continuation of these studies.

RESULTS: 1979

Although our original proposal to Wright Patterson AFB provided for one year of field work, the various delays that we encountered (belated Forest Service approval for the use of lasers and delayed availability of a "turning" mirror to direct the laser beam upward) limited the work that could be completed in 1978. Since the Langmuir Laboratory area was chosen by the International Commission on Atmospheric Electricity to be the site of the 1979 International Thunderstorm studies, we continued these laser studies for two months through the 1979 thunderstorm season as part of a cooperative effort.

Under this extension we leased a large, copper-coated, optical flat from Spawr Optical for use as the turning mirror. We also made arrangements for a French group consisting of Jean Louis Boulay, Pierre LaRoche, and Andre Eybert Berard to join us and to fire wire-trailing rockets into thunderclouds in a parallel effort to trigger lightning.

The Wright Patterson group headed by Jack Lippert and Capt. Charles Schubert arrived in late June and promptly began the preparation of the Air Force laser equipment for lightning triggering experiments. The turning mirror arrived July 23, 1979 and soon afterward the vertically-directed laser fire began.

In these attempts the laser was operated so that its beam was expanded at the source and then was brought to a focus for maximum effect at various heights up to about 500 m above the mountain top. Peak energies of up to about several hundred joules were delivered to the elevated focal region over a fraction of a microsecond. No visible lightning was triggered during the next 6 weeks of operation although r.f. emissions and audible sounds were detected in the subcloud regions above the laser.

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RESULTS: Continued

Later in the summer arrangements were made with FAA to permit activation of our restricted air space (R5113) during the nighttime in order that the optical effects of the laser on the atmosphere could be studied. On these occasions we observed up to 11 transient "beads" of luminosity arranged along the beam path in the vicinity of its focus. The beads were estimated to have diameter of the order of a large fraction of a meter and were separated along the beam path by distances of the order of 10 m. Several excellent photographs of these were obtained. A discussion of the physics of these plasma bodies will not be attempted here for this is the Wright-Patterson part of the cooperative experiment.

During this period we carried a new electric field meter with magnetic direction sensing to cloud base altitudes beneath a captive balloon so that we could detect the times when the electric field strength aloft were great enough for lightning triggering attempts.

Although no lightning was triggered by the laser during either summer, additional data on the deposition of charge in the lower part of a thundercloud by lightning were obtained with the balloon-borne instrumentation and these seem to support our hypothesis for the process.

The French group arrived in Socorro in August. As a result of a delay in passing their equipment through U.S. Customs they were not ready to fire rockets until August 16, their last day in New Mexico. Their activities were set up at the laser site in cooperation with the Wright-Patterson group.

The French equipment consisted of relatively small rockets (about 1 m long) that were arranged to fire vertically, accelerating at about 60 m/second² while towing a fine steel wire (about 0.15 mm in diameter) from a grounded bobbin up into the air. In the past the rapid injection of a grounded wire into a region with a strong electric field has caused the formation of plasma streamers that propagated outward from the top of the wire. In sufficiently strong fields these streamers have developed on their own and become a full lightning discharge.

By knowing exactly when the trigger rocket was to be launched, we hoped to have our radar, acoustic and electric field equipment all operating so that measurements could be made of these discharge processes.

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RESULTS: Continued

On the afternoon of August 16, 1979 an air mass thunderstorm developed over the Magdalena Mountains. After deciding that conditions were favorable for lightning triggering, Pierre LaRoche gave a fast countdown, launched one of his rockets, and triggered a major lightning discharge. Photographs and electric field data on this discharge were obtained. Unfortunately, the countdown was so rapid that much of the other equipment prepared for the lightning study was not turned on so that little data were obtained on this first discharge. About 75 minutes after the first triggered lightning, LaRoche reloaded the launcher and triggered another discharge. Although a widely held view is that triggered lightning is much less potent than is that in which breakdown occurs naturally, this second discharge produced the largest electromagnetic signals that we have ever measured with values of dB/dt in excess of 17 Teslas/second at distances in excess of 500 m. Natural lightning strikes to earth within 100 m of our measuring instruments have produced peak signals of only 5 Teslas/second during our measuring window.

A reconstruction of the triggered discharge and a TV photograph of it taken from Langmuir Laboratory about 1800 m to the SSE are enclosed.

An analysis of our electromagnetic signals (appendix I) indicates dipole moment accelerations associated with the breakdown processes with values in excess of 10^{13} Cm/sec². We plan to report on these results at the FAA, NASA and Florida Institute of Technology Symposium on Lightning Technology on 22 April 1980 at Langley Research Center Hampton Virginia.

The reduction of these measurements completed our work under this grant.

In summary the research carried out under AFOSR support included:

- 1) The installation and operation of a powerful laser that ionized columns of air beneath thunderclouds in attempts to trigger lightning.
- 2) The construction of a special electric field meter of the Winn design and its flights at cloud base level for determination of strong electric fields aloft and of the appropriate times for laser firings.

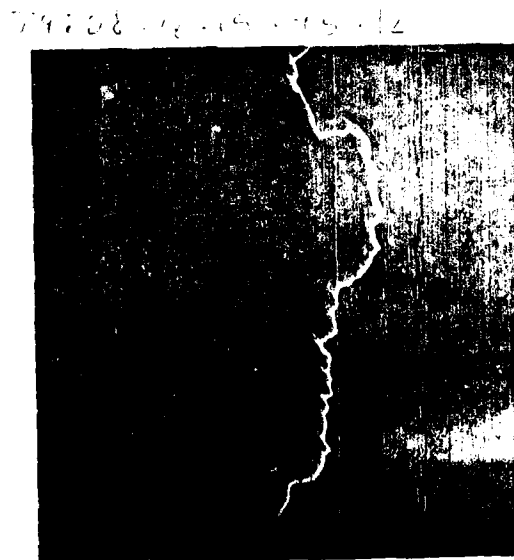


View of the second triggered lightning discharge from
the solar tower.

Date: 79228 M.S.T.: 1545.12



View of second triggered lightning discharge from
Langmuir Laboratory.



Peta 1 Sec 15.12

View of second triggered lightning discharge from
the Kiva.

Date: 79228 M.S.T.: 1545.12

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RESULTS: Continued

3) The discovery that some of the electric field excursions associated with precipitation previously observed by Moore et.al. are a result of the deposition of charge by lightning onto precipitation particles. The sequence is usually terminated by a second discharge that seems to be a result in part of the downward fall of the charged precipitation.

4) The successful triggering of lightning by wire-trailing rockets. The French have apparently made a happy choice of rocket acceleration, burn times and terminal velocities such that the critical speeds necessary for triggering of lightning are exceeded without the high accelerations that have caused most of NASA's and other agencies' efforts to fail.

We intend to continue our lightning triggering attempts and the studies of the resulting discharges.

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APPENDIX I

ANALYSIS OF ELECTROMAGNETIC SIGNALS RECEIVED AT THE IRON KIVA

Sensor Location

Electromagnetic sensors of dB/dt and dD/dt * are mounted on the roof of the buried, electromagnetically-shielded room known as the Kiva, on top of South Baldy Peak at the crest of the Magdalena Mountains of Central New Mexico. These sensors, the MGL-3, for dB/dt and the ACD-5, for dD/dt were supplied by the Air Force Weapons Laboratory for this study.* The 6 m diameter, flat, metal roof of the iron Kiva is in the center of and connected to a metal, mesh surface that extends radially outward to produce a 30 m square ground "plane". The center of the B(East) sensor on the Kiva roof is about 2 m NE of the roof center and its axis is oriented accurately on a geographical East-West line such that an eastward-directed $\dot{B}$ signal gives a positive voltage signal out on the central conductor of its GR 874 output connector. The $\dot{B}$ (North) sensor on the roof is located with its center about 1.5m WNW of the Kiva roof center and is oriented along a geographic North-South line such that it outputs a positive signal for a northerly-directed B signal. The $\dot{D}$ sensor is located about 1.7m south of the Kiva roof center. Its axis is vertical so that it responds to vertical components of the electrical displacement vector. A positive value for dD/dt produces a negative signal at the center electrode of the 50 ohm output terminal in the base of the

*In this report for brevity, dB/dt will frequently be denoted as B and dD/dt similarly will be indicated as D.

sensor. The separations of the sensors on the Kiva roof, therefore, are of the order of 3.6m.

The signals from the sensors are led through GR 874, 50 ohm feed-throughs and RG/8 coaxial cable in the Kiva roof to Biomation 8100 waveform analyzers within the Kiva. The coaxial cable lengths for the sensors are 8.3m for B(East), 7.8m for B(North), and 6.8m for D. The time differences of arrival of signals at the waveform analyzers may therefore be as great as about 25 ns depending on the orientations, relative to the sensors, of the sources from which the signals came.

Signal Recording

The Biomation waveform analyzers were triggered internally by incoming signals that exceeded a predetermined threshold (usually set to be either 0.2 or 0.4 of the instrument's full scale of measurement). The analyzers were cross-connected so that when the input signals triggered any one of them, they all recorded data. The incoming signals were digitized continuously during this period with a 10 ns resolution in time and with 7 bits plus polarity in magnitude. The digitized signals in each waveform analyzer were fed into an internal 2048 byte shift register arranged so that, when a trigger occurred, about 4 μ s of data prior to the trigger were saved together with 16 μ s of data after the trigger. The waveform analyzers recirculated the 20 μ s of data storing them temporarily until they could be transferred into a HP 9825 mini-computer controller.

Upon completion of the digitization, a "flag" signal was sent to the HP 9825 that then transferred the shift register data from each waveform analyzer, in turn into the memory of the HP 9825 which then re-armed the Biomation devices in preparation for collection of the next signals strong enough to re-trigger the waveform analyzers. After re-arming the Biomation instruments, the HP 9825 stored the first set of data on magnetic discs for later analysis. In this mode of operation, an interval of about 25 milliseconds was required to collect a set of data from the 4 Biomation analyzers and then to re-arm them for a second "data-grab" from the same lightning flash that provided the first trigger. By operating in this mode we attempted to obtain data on the initiating, stepped-leader process and then, in the second grab, data on a subsequent return stroke in the same flash.

Instrumental difficulties prevented the second data grab during most of the flashes in the 1978 and 1979 summers so that this desirable "double-grab" system is still being developed.

Data Presentation

In each of the case studies that follow, the original data have been plotted out with corrections for the sensitivity settings of the waveform analyzers and for power splitters (when they were used) so that the sensor output voltages are displayed as of functions of time for the three recorded variables. In the second set of plots for each case study, the voltage outputs have been interpreted in terms of the B and D

signals that produced them. Since B varies but little over the 0.1m area S of the magnetic sensors,

$$\dot{B}[\text{EAST}] = \Delta V_E / S \quad \text{and} \quad \dot{B}[\text{NORTH}] = \Delta V_N / S.$$

The D antenna senses the vertical component of the displacement. From Maxwell:

$$\begin{aligned} \nabla \cdot [\nabla \times \vec{H}] &= \nabla \cdot (\vec{J} + d\vec{D}/dt) = 0 \\ \therefore \int_S \vec{J} \cdot d\vec{S}_D &= - \int_S (d\vec{D}/dt) \cdot d\vec{S}_D = I_{\text{out of sensor}} = \Delta V_D / 50 \Omega. \end{aligned}$$

The effective area (S_D) for the dD/dt sensor is 1m^2 .

The data stored by the 9825 mini-computer were in digital form so that it was easy to integrate them and to determine the magnitudes of the dB/dt, dD/dt, B and D vector components at the surface of the Kiva. Plots of these are shown for each case study.

From other recordings on magnetic tape, the total electric field changes produced by each flash can be determined as can the time and nature of the subsequent thunder. The range to the portion of the discharge closest to the thunder microphone at the Kiva was determined for each flash in this manner.

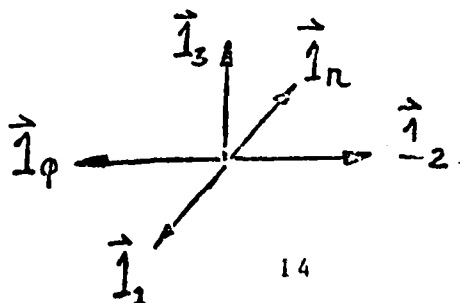
During the 1978 summer, triggers from 74 flashes occurred for which dB/dt data were recorded. The waveform analyzer for the dD/dt signals during this period malfunctioned so that the digital dD/dt data could not be recorded directly. The dD/dt data were recorded in analog fashion on an x y plot-

ter and later digitized manually. These digital data were arranged by interpolation into evenly spaced intervals and transferred serially into the memory of the 9825 calculator for comparison with the dB/dt data on the same time bases but this technique degraded the original data.

During the 1978-1979 winter, the defective signal transfer system on the dD/dt waveform analyzer was repaired so that in the 1979 summer thunderstorm season, 90 triggers occurred with the direct digital recording of both dB/dt and dD/dt data.

Analysis of Data

With these data, it has been of interest to attempt determinations of the locations and polarizations of the sources that produced the signals by use of the method described by Baum, et al (1980): Each signal that we receive can have originated anywhere in the hemisphere over the Kiva and can have been produced by charge accelerations with all possible orientations except those on a radial line from the Kiva (for these, in the far field, do not propagate toward the Kiva). Accordingly, we define a spherical coordinate system with radial position vector r that has zenith angle Θ , and azimuthal angle φ measured counter clockwise from geographic North. A second coordinate system, local to the putative source and perpendicular to our line of sight from the Kiva, is defined as:



In this second system, the direction of $\vec{l}_1$ is defined as $-\vec{l}_N$, radically inward, toward the Kiva, $\vec{l}_2$ is toward the observer's right when he looks up toward the source ($\vec{l}_2 = -\vec{l}_\varphi$) while $\vec{l}_3$ is the upward direction, perpendicular to the observer's line of sight from the Kiva. With the use of this second coordinate system, we can resolve all electromagnetic, plane waves received at the Kiva into two orthogonal components, one with the electric vector $\vec{E}$ parallel to the horizontal top surface of the Kiva i.e. a transverse electric vector, $(\vec{E}^{(TE)})$, and the other with a horizontal magnetic vector i.e. a transverse magnetic vector, $(\vec{B}^{(TM)})$.

For each signal, there are 5 defining variables of interest:

$$r, \theta, \varphi, dB^{(TE)}/dt \text{ and } dB^{(TM)}/dt,$$

but we have only 4 independent measurements for each pulse: the distance r to the nearest thunder source, dB_r/dt , dB_E/dt and dB_H/dt .

We can obtain some constraint relations between the variables by analysis of the properties of the TE and TM waves:

1) Over a conducting plane, the magnetic indications of the sensors are twice those of the incident, horizontal components of the magnetic flux due to the image currents.

2) While $\dot{B}^{(TM)}/dt$ couples in directly to the horizontal B sensors, $\dot{B}^{(TE)}/dt \cos \Theta$ is the only component from a TE wave that is detected by the magnetic sensors.

Our coordinate system (with the reference direction being toward the North) is defined by

$$\hat{x} = \text{North} = \hat{N}$$

$$\hat{y} = \text{West} = \hat{W}$$

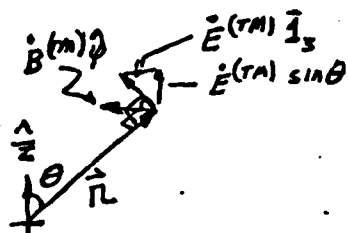
$$\hat{z} = \text{Zenith direction}$$

$$\text{and } \dot{B}_W = -\dot{B}_E$$

We define Ψ as the horizontally, radial direction outward from the Kiva in cylindrical coordinates:

$$\text{Therefore } \dot{B}_N \hat{x} + (-\dot{B}_E) \hat{y} = 2 \left[\dot{B}^{(TE)} \cos \Theta (-\hat{\Psi}) + \dot{B}^{(TM)} \hat{\rho} \right].$$

The TE wave does not couple into the sensor of dD/dt since this component of $\vec{D}$ and the sensor axis are orthogonal but we do sense the vertical component of $\vec{D}$, doubled at the Kiva surface by its image in the ground plane.



Therefore: $\left(\frac{dD_z}{dt} \right)_{\text{incident}} = \left(\frac{dD^{(TM)}}{dt} \right) \sin \theta$

From Lorentz, $|\vec{E}| = |c \vec{B}|$

and $|\vec{D}| = |\epsilon_0 \vec{E}| = |\epsilon_0 c B^{(TM)}| = |D_{z_{KIVA}} / 2 \sin \theta|$.

Therefore, $\sin \theta = \left(\frac{dD_{z_{KIVA}}}{dt} \right) / 2 \dot{B}_{\text{INCIDENT}}^{(TM)} \epsilon_0 c = Z_0 \dot{D}_{z_{KIVA}} / 2 \dot{B}_{\text{INCIDENT}}^{(TM)}$

where $Z_0 = 376.73$ ohms, the "impedance" of free space.

We can plot the allowable solutions for θ and φ from these relations by rotating the orthogonal components $\dot{B}(N)$ and $\dot{B}(W)$ incrementally through 360 degrees in azimuth. For each trial azimuth, we solve for the resulting values of $B^{(TE)} \cos \theta$ and $B^{(TM)}$ which we then use to calculate the required value of zenith angle from:

$$\theta(\varphi) = \arcsin \left(Z_0 \dot{D}_{z_{KIVA}} / 2 B_{incident}^{(TM)} \right).$$

The polar plots of θ and φ shown for each case study were obtained in this manner.

The distances that streamers associated with initial breakdown processes in lightning can move in intervals of a few microseconds are probably of the order of 100 meters or less so that θ and φ for a source often may change relatively little between successive $\dot{B}$ & $\dot{D}$ pulses. When this condition is met, the loci of the θ and φ polar plots for a succession of pulses may intersect and thus indicate a solution for the allowable θ and φ angles from the Kiva toward the elevated source.

We have tried this technique with these data and find that, often, the same approximate values for θ and φ fit the data for many pulses associated with a leader streamer. On the other hand, the data for successive pulses in a return stroke often give relatively poor indications of a quasi-fixed position for a common source for these events, as might be expected from the high propagation velocity of a return stroke.

From the favored choice for Θ and φ for a given leader event, we are then able to estimate values for $B_{INCIDENT}^{(TE)}$ and for $B_{INCIDENT}^{(TM)}$ and for their integrals over each pulse from:

$$\begin{aligned} \left[\frac{d\vec{B}^{(TE)}}{dt} \right] \cos\Theta &= 0.5 \left[\left(\frac{dB_N}{dt} \right) \cos\varphi - \left(\frac{dB_E}{dt} \right) \sin\varphi \right] \hat{Y} \\ \frac{d\vec{B}^{(TM)}}{dt} &= 0.5 \left[- \left(\frac{dB_N}{dt} \right) \sin\varphi - \left(\frac{dB_E}{dt} \right) \cos\varphi \right] \hat{\varphi} \\ \text{and } \left[\frac{dB^{(TE)}}{dt} \right] \hat{I}_3 &= - \left[\frac{\left(\frac{dB^{(TE)}}{dt} \right) \cos\Theta}{\cos\Theta} \right] \hat{I}_3 \end{aligned}$$

Note that an inwardly directed $\frac{dB^{(TE)}}{dt} \cos(\hat{Y})$ indicates an upwardly directed $\left(\frac{dB^{(TE)}}{dt} \right) \hat{I}_3$.

Our best estimate for the slant range, r_e to the appropriate portion of a lightning discharge that strikes the earth (approximately perpendicularly) is based on the assumption that the time-to-first-thunder represents the horizontal distance from the Kiva microphone to the closest part of the channel and therefore the slant range r , assumed is

$$r_e \approx (340 \text{ m/s}) \Delta \text{time} / \sin \Theta.$$

From these data, we have obtained estimates for the location and polarization of the sources of the electromagnetic waves produced by sections of lightning streamers.

The Time Derivative of The Integral of the Current Density Over the Source Volume, $\dot{I}$.

The final step in this analysis has been to take these values for $B^{(TE)}$, $B^{(TM)}$, M , θ and φ to reconstruct a projected view of the source streamer based on the Green's function derivation given by Baum (1976). From electromagnetic theory, the retarded vector potential A is given by:

$$\vec{A}(\vec{r}', t) = \frac{\mu}{4\pi} \int_{\text{volume}} \left[\frac{\vec{J}(\vec{r}, t^*)}{r} \right] d\text{vol}.$$

Since $E = -\nabla\Phi - \partial\vec{A}/\partial t$ the component E_A contributed by the vector potential at $(\vec{r}, t)$ that was produced by $\vec{J}(\vec{r}, t^*)$ is given by:

$$\vec{E}_A = -\partial\vec{A}/\partial t = -\frac{\mu}{4\pi} \frac{\partial}{\partial t} \int_{\text{vol}} \left[\frac{\vec{J}(\vec{r}, t^*)}{r} \right] d\text{vol}.$$

Again from Lorentz $|\vec{E}_A| = |c \vec{B}|.$

Therefore

$$|c \vec{B}_{\text{INCIDENT}}| = \frac{\mu}{4\pi} \left| \frac{\partial}{\partial t} \int_{\text{volume}} \left[\frac{\vec{J}(\vec{r}, t^*)}{r} \right] d\text{vol} \right|.$$

If $\vec{r} \approx$ constant over the source volume, we can write, in vector form, for an incident plane wave propagating through the atmosphere:

$$\frac{4\pi c}{\mu_0} \left[\left(\frac{d\vec{B}^{(E)}}{dt} \right) \times \vec{n} \right] = \left[\frac{\partial^2}{\partial t^2} \int_{vol} J_\varphi dvol \right] \hat{\varphi}$$

and

$$\frac{4\pi c}{\mu_0} \left[\left(\frac{d\vec{B}^{(E)}}{dt} \right) \times \vec{n} \right] = \left[\frac{\partial^2}{\partial t^2} \int J_3 dvol \right] (-\vec{1}_3).$$

Since we wish to work with individual pulses, we select the change associated with each signal and use $\Delta[B^{(TE)}/dt]$ $\Delta[B^{(TM)}/dt]$ in the reconstructions.

For simplicity of nomenclature, we now define the time derivative of the volume integral of the current density vector at the signal source as the vector quantity "Upsilon": Υ .

Therefore:

$$\left[\frac{\partial^2}{\partial t^2} \int_{vol} J_2 dvol \right] = - \frac{4\pi R C}{\mu_0} \Delta \dot{B}_{INCIDENT}^{(TE)} \equiv \dot{\Upsilon}_2$$

and

$$\left[\frac{\partial^2}{\partial t^2} \int_{vol} J_3 dvol \right] = - \frac{4\pi R C}{\mu_0} \Delta \dot{B}_{INCIDENT}^{(TM)} \equiv \dot{\Upsilon}_3.$$

Reconstructions of the streamer projections-based on this model-are included in the case studies. In these reconstructions, we plot each projected value of $\dot{\Upsilon}$ as the direction of a positive current element. For negatively charged leader streamers where the direction of streamer propagation is opposite to that of the positive current element, we plot the head of the first $\dot{\Upsilon}$ vector at the center of the field of view in $\vec{i}_2$ and $\vec{i}_3$ coordinates and place the head of the second $\dot{\Upsilon}$ vector on the tail of the first vector and so on to depict the

view of this portion of the negative streamer from the Kiva. For positive streamers (as in return strokes and in triggered lightning), the reconstruction process is reversed with the vectors added normally: the tail of the first $\vec{I}$ vector is placed on the head of the first to indicate propagation in the direction of the projected current element. In both cases, the individual vectors are also plotted for comparison: each pulse and resulting vector are identified by the time, in microseconds within the event that the pulse occurred.

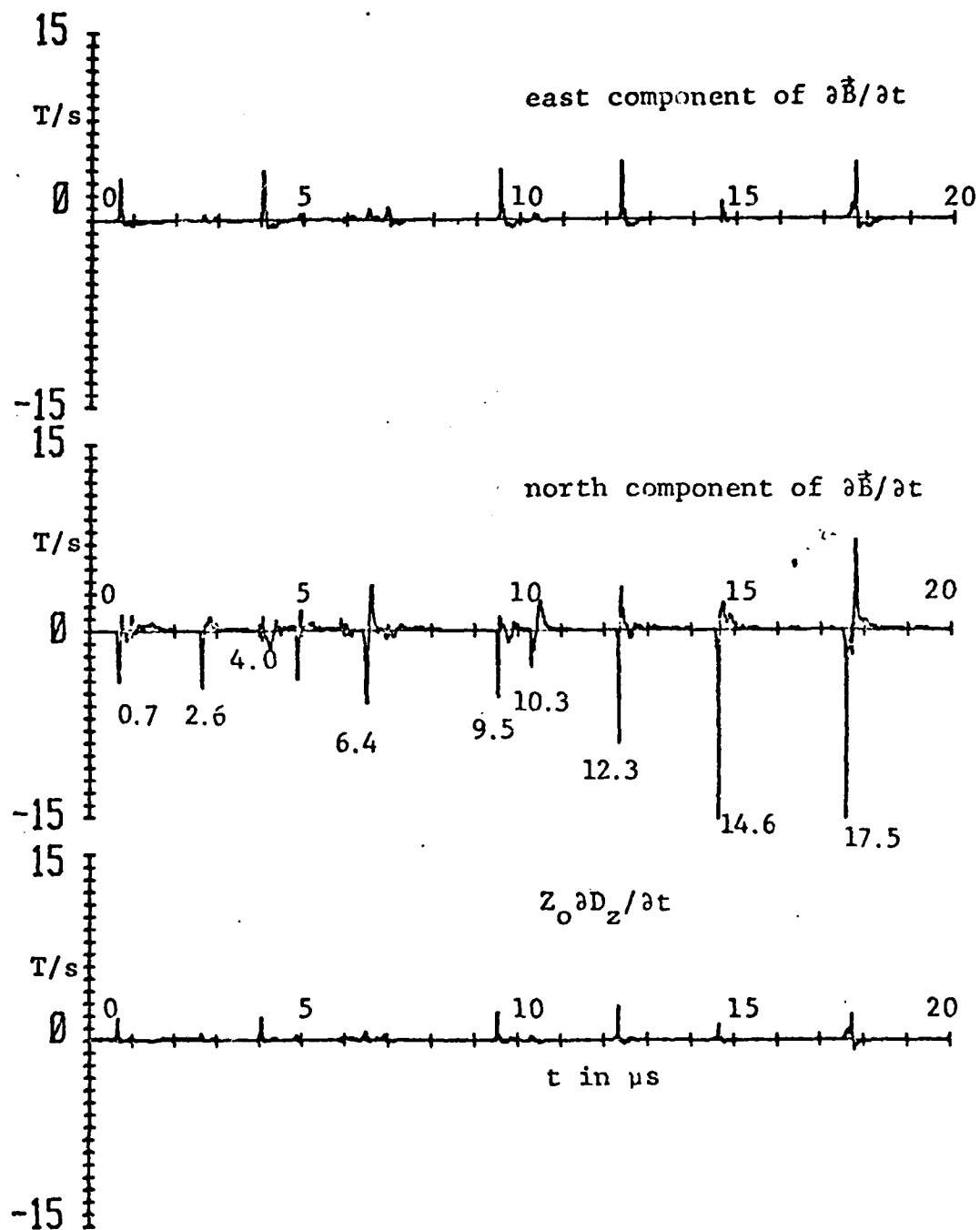
The entire procedure is repeated for the time integrals of the dB/dt and dD/dt pulses to obtain vector plots of $\vec{I}$ itself.

D. L. Hall

C.B. Moore

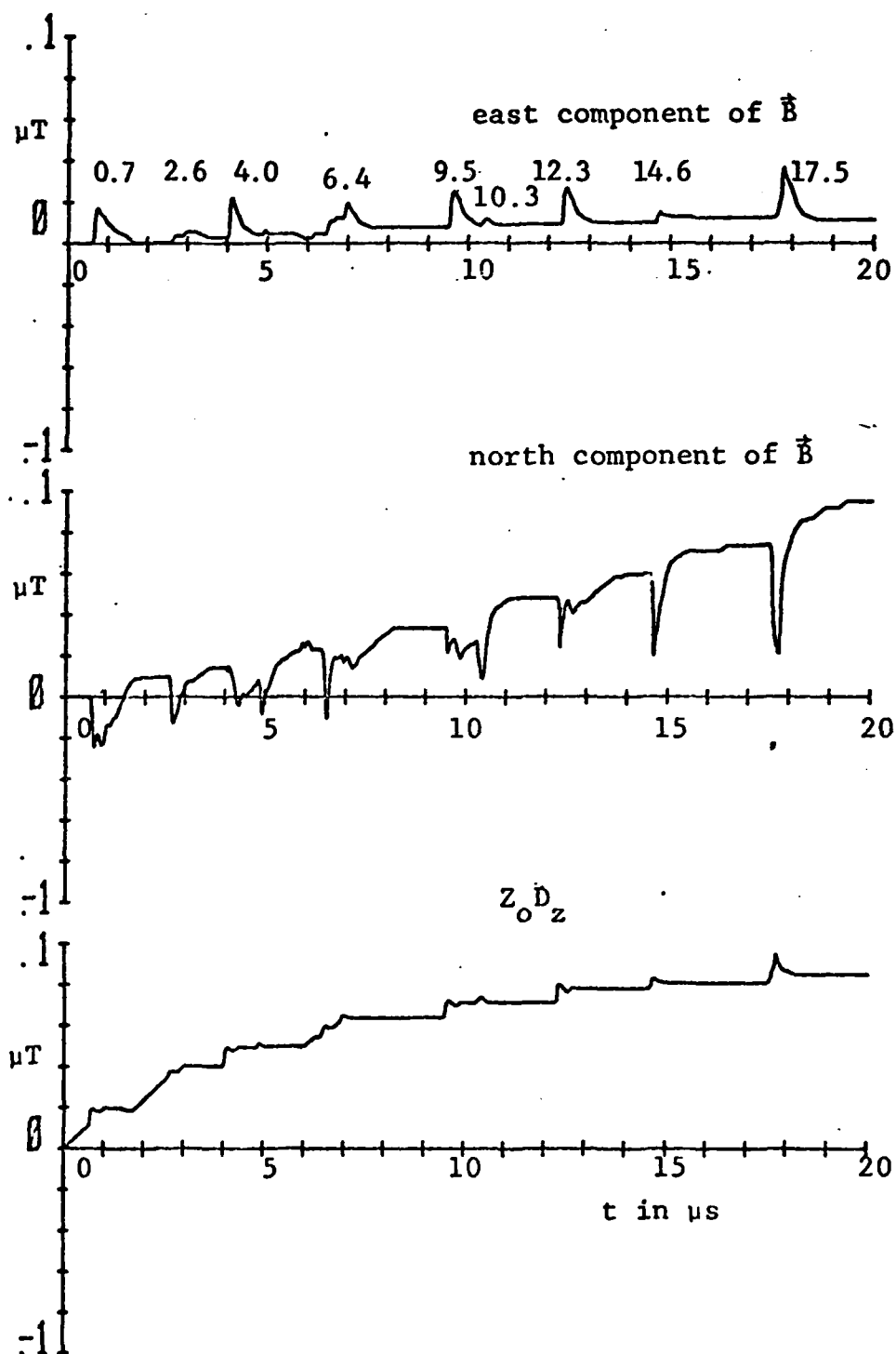
New Mexico Tech

Socorro, New Mexico 87801



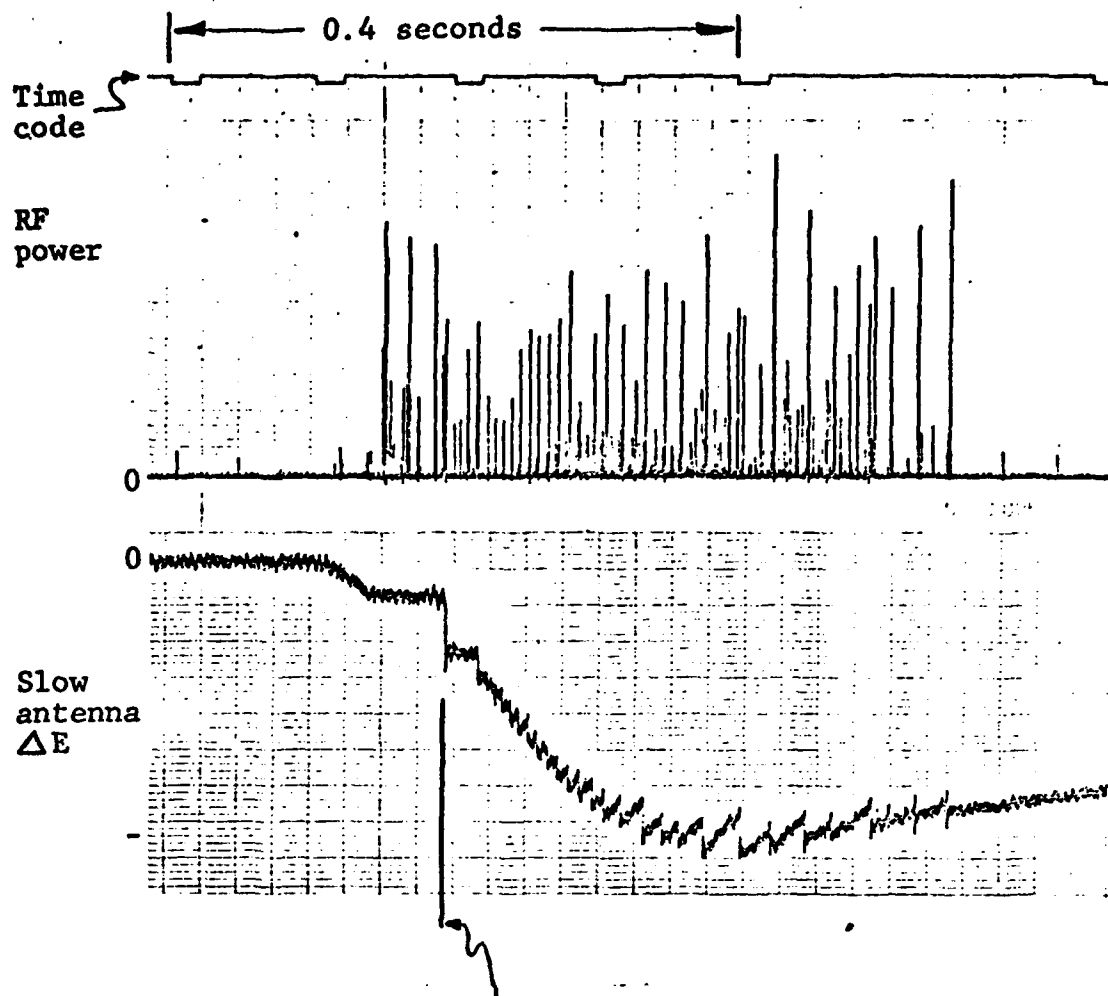
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Figure A-1 Derivative fields from rocket-triggered lightning



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Figure A-2 Fields from rocket-triggered lightning



Horizontal range from Kiva to rocket launcher : 350 m

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Figure A-3 Slow electric field change and RF power received at 54 MHz from rocket-triggered lightning

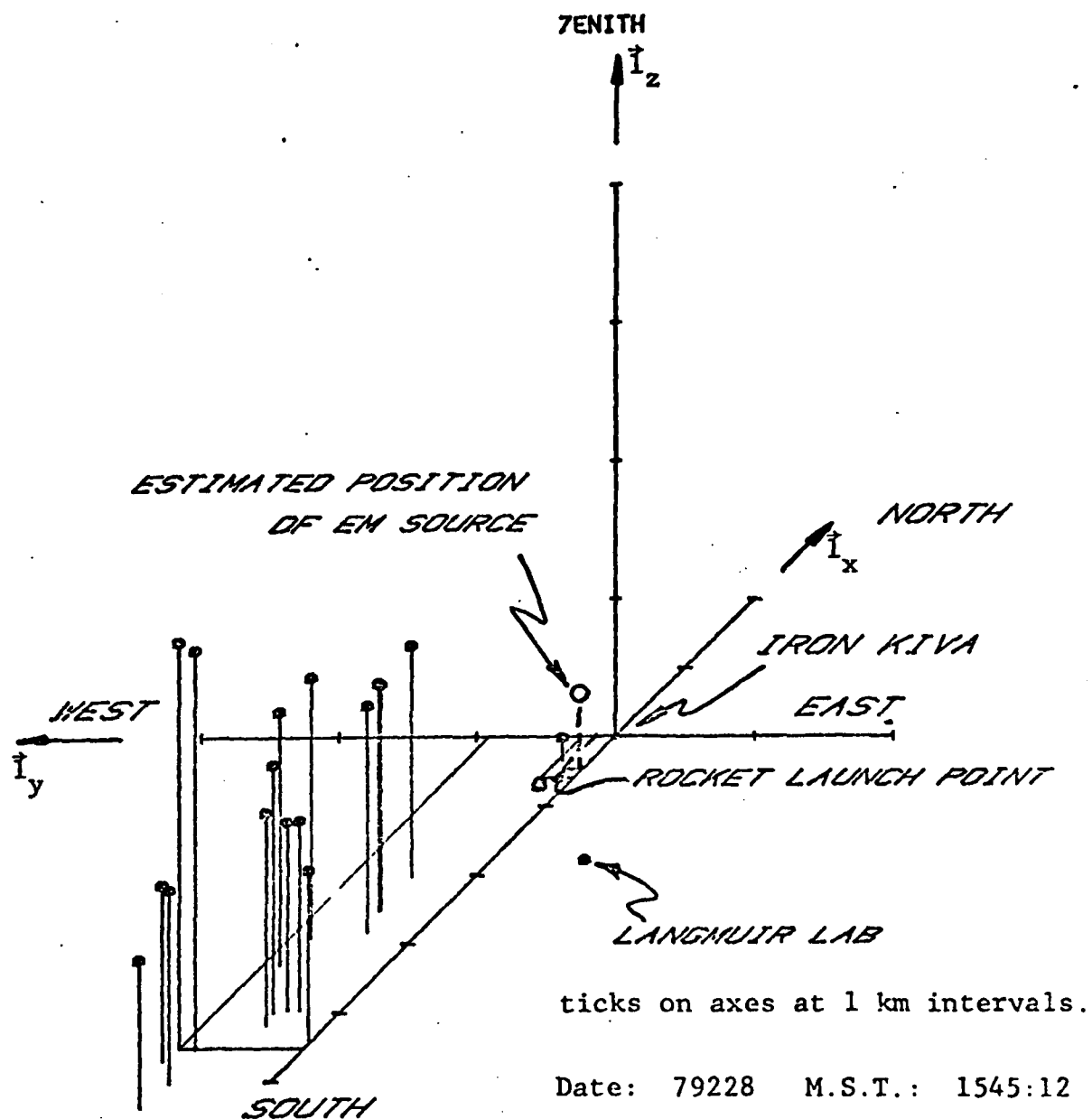


Figure A-4 Acoustic location of rocket-triggered lightning

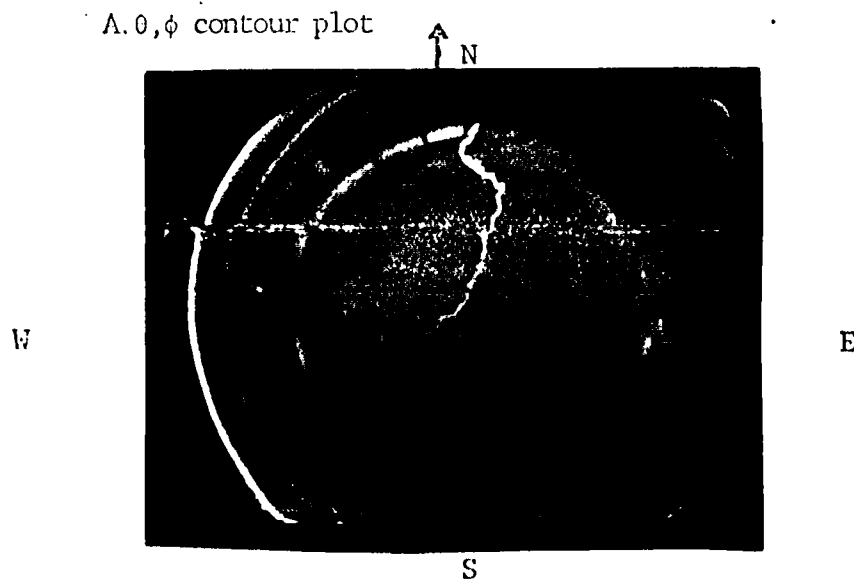
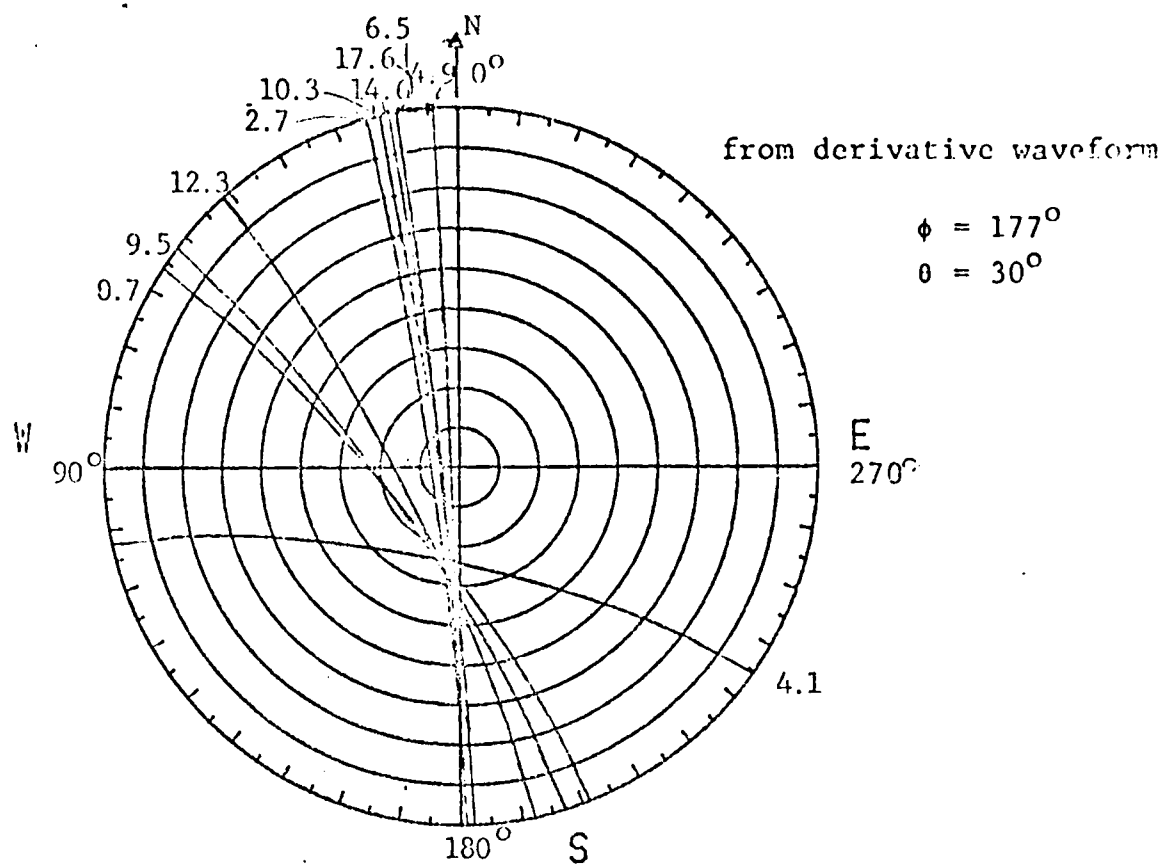
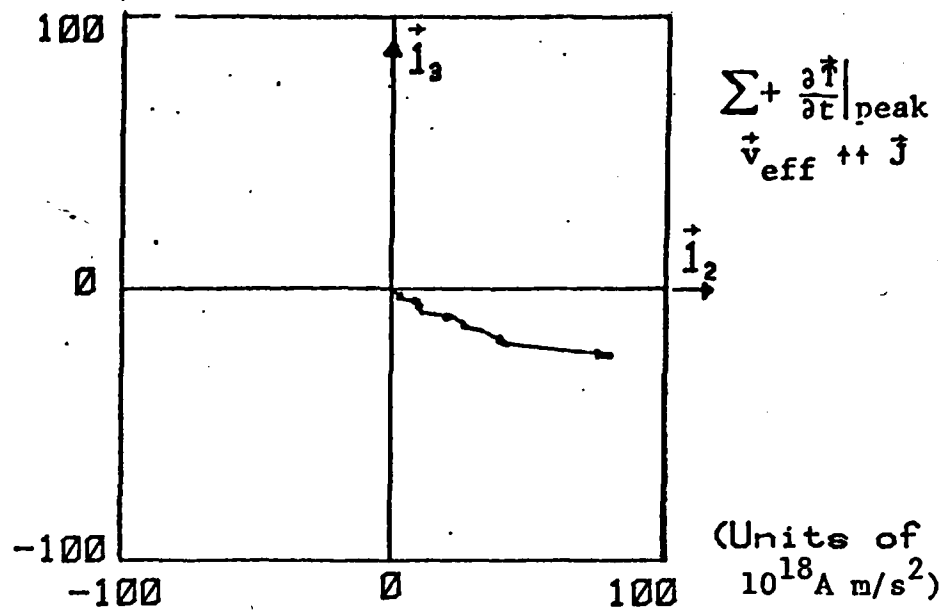
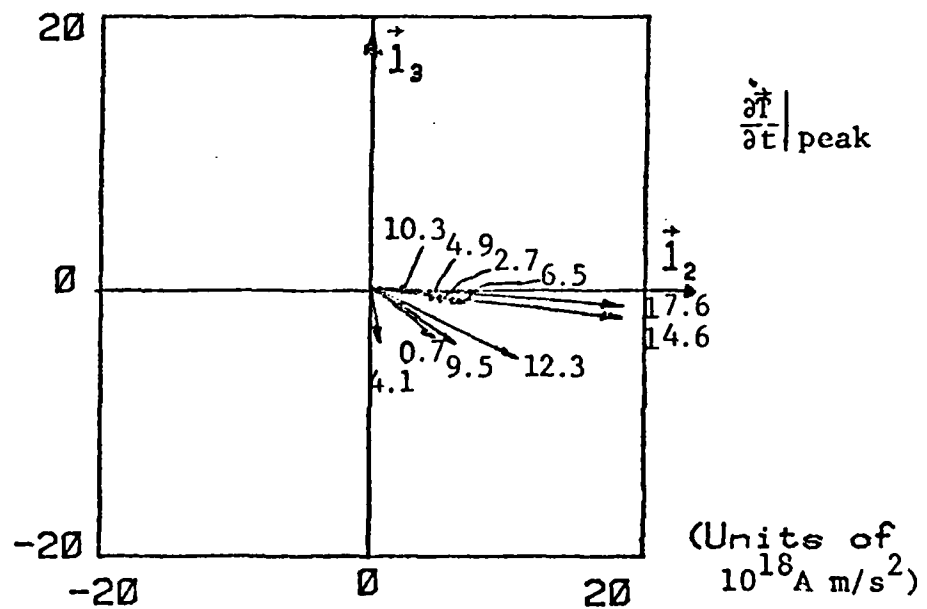


Figure A-5 θ, ϕ contours for rocket-triggered derivative waveform and whole-sky videotape photograph



A. Effective reconstruction of positive streamer

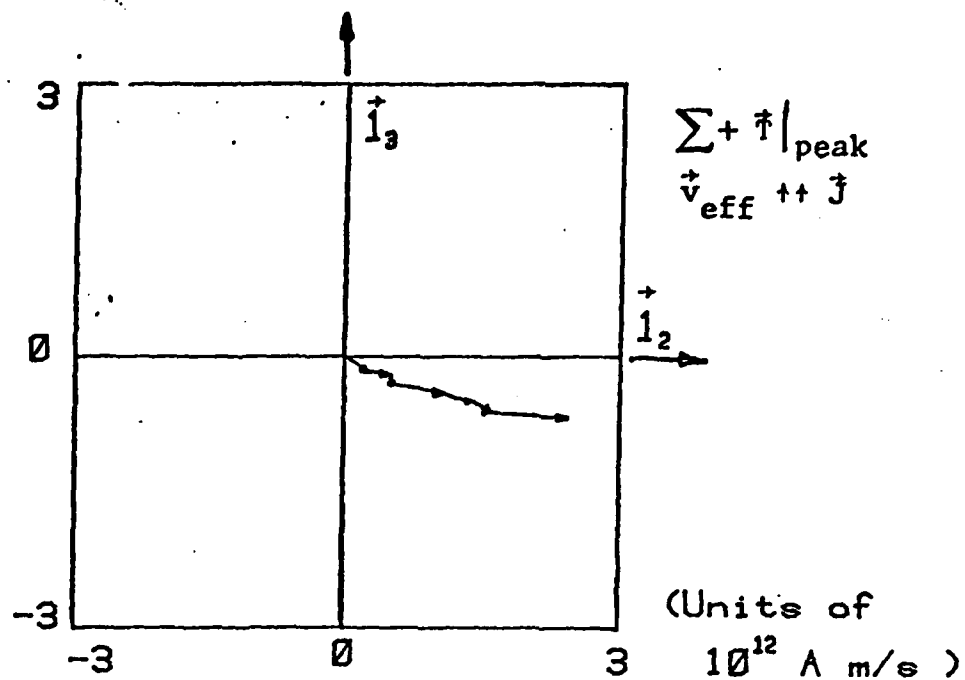


B. Peaks of $\frac{\partial \vec{I}}{\partial t}$

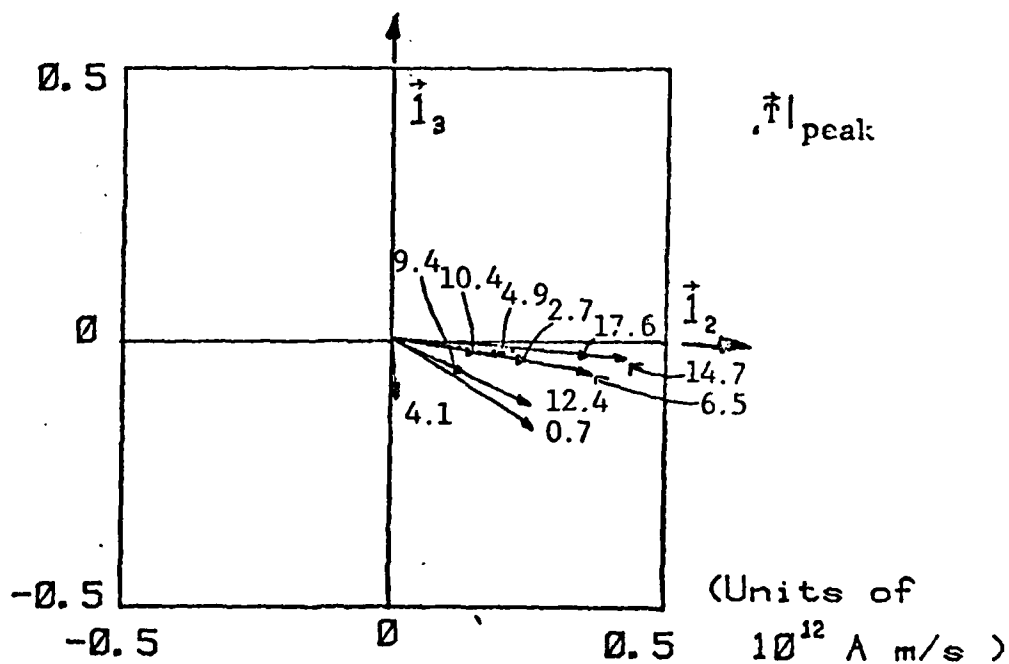
$\phi = 177^\circ$, $\theta = 30^\circ$, $r = 700\text{m}$

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Figure A-6 $\frac{\partial \vec{I}}{\partial t}$ for rocket-triggered lightning



A. Effective reconstruction of positive streamer



B. Peaks of $\vec{i}$

$\phi = 177^\circ$, $\theta = 35^\circ$, $r = 610\text{m}$

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Figure A-7 $\vec{i}$ for rocket-triggered lightning

APPENDIX II

LOCAL CHARGE CONCENTRATIONS IN THUNDERCLOUDS*

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The existence of a lower positive charge center in thunderclouds was inferred by Simpson and Scrase (1937) from their alti-electrograph data. This lower positive charge is not always observed in thunderclouds; it appears to be transient and usually associated with rain.

Some of our observations and those of Jacobson and Krider (1975) suggest that some of these localized positive charges may be caused by lightning: when a lightning flash occurs in a thundercloud directly over our net of electric field meters, we occasionally observe an anomalous behavior in the electric field immediately after the discharge. Instead of the usual smooth recovery to its original, foul-weather value after the lightning-induced field discontinuity, sometimes the local electric field directly below a portion of the discharge retains the fair weather polarity and even intensifies for several minutes while the surface fields at distances of 2 or 3 km recover normally to their predischage, foul-weather strengths. When this anomaly occurs, a burst of precipitation often arrives at the earth about 3 minutes later and then the field makes its delayed recovery to the original foul weather intensity. Typically, another, nearby discharge occurs in the lower regions of the thundercloud to terminate the sequence.

We interpret the localized, anomalous electric fields as the result of the deposition of positive charge in the lower regions of the cloud where some of it becomes attached to precipitation and then falls out. The normal recovery of the fields at locations relatively distant from the discharge is interpreted as evidence that the principal negative charge generator in the cloud continues to operate during the sequence. The fallout of the positively charged precipitation and the action of the negative charge generator then cooperate to produce the 'terminal' lightning flash.

The magnitude of the electric field excursion at the earth during this sequence is not directly correlated with the subsequent intensity of the precipitation: we have observed large and sustained reversals in the electric field after a nearby flash followed by rain of 10 millimeters per hour or less. The amounts of charge transported downward by rain after one of these anomalous discharges are estimated to be of the order of 1 coulomb.

The effect may not be limited to positive charges or to the lower regions of thunderclouds: with the use of Faraday cups mounted on top of free balloons, we have observed an anomalous burst of negatively-charged precipitation in the upper portions of a thundercloud shortly after the nearby passage of a lightning streamer. Similarly, since the phenomenon is detectable only at short ranges, it may occur much more frequently in thunderclouds than has previously been inferred from single station observations.

*This paper has been accepted for presentation at the VI International Commission on Atmospheric Electricity at Manchester, England, July 27-August 1, 1980.