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SYNTHESIS OF ATMOSPHERIC ELECTRICITY OBSERVATIONS: A THUNDERSTORM ON JULY 22, 1977, IN FLORIDA; DAY 77203 TRIP 77, KENNEDY SPACE CENTER

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SYNTHESIS OF ATMOSPHERIC ELECTRICITY OBSERVATIONS:
A THUNDERSTORM ON JULY 22, 1977, IN FLORIDA;
DAY 77203 TRIP 77, KENNEDY SPACE CENTER

by

Arvin Clarence Conrad, Jr.

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

DOCTOR OF PHILOSOPHY

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MAY, 1985
SYNTHESIS OF ATMOSPHERIC ELECTRICITY OBSERVATIONS: A THUNDERSTORM ON JULY 22, 1977, IN FLORIDA; DAY 77203 TRIP 77, KENNEDY SPACE CENTER

Arvin C. Conrad, Jr.

ABSTRACT

Observations of an air-mass thunderstorm occurring July 22, 1977, during the Thunderstorm Research International Program (TRIP-77) at Kennedy Space Center (KSC), Florida are interpreted. These observations yield insight into storm dynamical and electrical mechanisms and their interrelationships.

The dynamics of this storm are markedly different from that of the classical picture of an isolated convective system. The observed air-mass cells exhibit dynamic and electric changes on time and spatial scales that are significantly smaller than described in textbook examples: time scales on the order of 10 rather than 30-90 minutes and areal extents on the order of < 4 km rather than 6-10 km. Fast scanning radar (NMIMT-REDBALL) images indicate that dynamic periodicity is produced by rapid buoyant-bubble growth.

Comparison of acoustic and radio frequency (RF) derived source locations suggest that these techniques depict entirely different scale phenomena. The RF (KSC-
REAL TIME LDAR) consistently located sources higher in the cloud than the concurrent thunder locations. These thunderstorms produce copious quantities of RF radiation from small discharge processes that are not classically considered lightning (i.e., a flash of light followed by thunder). There is temporal complementarity (anticorrelation) in the activity profiles of the small upper-cloud discharges and lightnings; i.e., RF "sizzle" precedes lightning that produces an acoustic "bang".

When acoustic source locations for sequential events are overlaid, the volumes depicted by these loci seek or fill disjoint yet contiguous regions rather than repeatedly discharging the same volume. This is important to considerations of thunderstorm charging rates because the lightnings are not discharging the same volume, hence, cloud volume recharging between events is not necessary.

The inherent temporal and spatial "granularity" in the data acquisition makes data comparisons difficult which inhibits the ability of such experiments to resolve questions of cloud electrification. The testing of these hypotheses requires highly resolved ground based observations and in situ microphysical and electrical measurements. Attention to simultaneity in data acquisition is paramount in the design of cooperative thunderstorm electrification studies.
PREFACE

Computers and applications programming have been the greatest stumbling block throughout much of the data reduction process over the years that this paper evolved. Always there has not been sufficient memory capacity or speed or hardware reliability. This group has always depended on hand-me-down government property for its hardware resources. In the fall of 1983, through the auspices of Mr. Bill Holbert of the Perkin-Elmer Data Products Division, we acquired via a very beneficial arrangement, a modern mini-computer and a version of Bell Laboratories UNIX operating system. Much of the effort of this author since January 1984, has been devoted to the installation of this system. The transition from the earlier environment to this new state has been arduous but is now nearly complete from the system standpoint. However the task of porting the entire set of data reduction packages, especially the graphics, still lies ahead.

From the preliminary indications this new system will be very powerful and certainly much quicker in response than the earlier ones. Definitely it is more rational and congenial. Ideally during subsequent field experiments a computer of sufficient power and capability would be included to help acquire and validate data on a day to day
near-real-time basis.

This thesis was composed and managed entirely on the Perkin/Elmer UNIX system. It was printed on an Imagen 8/300 Laser printer.
ACKNOWLEDGEMENTS

I wish to acknowledge the tremendous support and assistance from the following:

Dr. Arthur Few, my advisor, and his family for their help, encouragement, and hospitality;

Mike Stewart, P.E.,
Jerry Bohannon, Andy Weinheimer,
Greg Byrne, Richard Torczon;

NASA, NSF, ORNL for supporting this endeavor;

(Grants and contracts directly supporting various aspects of this research are: NSF ATM-8111715, ATM-8016164, ATM-7617913, and ONR N 00014-77-C-0154.)

Dr. Marx Brook,

New Mexico Institute of Mining and Technology;
Carl Lennon, Kennedy Space Center NASA for the LDAR data;
Kennedy Space Center personnel at TRIP 1977;
NMIMT personnel during TRIP 1979, and TRIP 1981;
National Severe Storms Laboratory personnel in 1983;
Rice University Space Physics and Astronomy Department;
the craftsmen and instrument makers who tutored me and executed my designs;
the many patient relatives, friends; and,
Geri Aramanda for "11th" hour editorial assistance.
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INTRODUCTION

0.0. GOALS

The overall goal of the study of thunderstorm electricity is to increase the understanding of the link between the electrical, microphysical, and dynamical mechanisms operating in the thunderstorm environment. One goal of this thesis is to report on observations conducted by the Atmospheric Research group from Rice University Space Physics and Astronomy Department during the summer of 1977 at Kennedy Space Center, Florida (KSC). Specifically we will concentrate on a thunderstorm which occurred during the afternoon of July 22, 1977 (DAY 77:203).

Another major thrust of this thesis is to combine into a coherent context several sets of concurrent observations made during this storm by several investigators. The resources for this task are derived from the efforts of the many Principal Investigators and workers who participated in the Thunderstorm Research International Program (TRIP) conducted in Florida in 1977.

Previously a concerted effort has been made to bring together observations of a single electrical event which occurred during a cooperative observing period,
TRIP 76 at Kennedy Space Center in Florida [Uman, et al., 1978].

However, this thesis is novel in its accomplishment of bringing together data from a larger scale episode and in its efforts to handle such a wide variety of data formats.

Cooperative programs, such as TRIP, have as their basic mission the simultaneous observation of thunderstorm phenomena and the synthesis of such findings into a better understanding of the storm. This then is also the goal of this thesis for the events of July 22, 1977. This is the ideal expectation; it will become obvious in the course of the ensuing discussions that there are difficult problems associated with utilizing other investigator's data. One of the early conclusions of the discussion is that greater attention should be paid to data analysis procedures during the initial planning phase of such cooperative field programs.

The hostile weather environments encountered in and beneath active thunderstorms add difficulty to the data acquisition. Principal Investigators usually have diverse thunderstorm research interests and consequently they focus their attention on different facets of the storm. Individual experimental techniques differ widely in their acquisition characteristics; e.g., range, sensitivity, data rates, and graphical representation format. Consequently
the available data are not always as comprehensive or coherent as initially desired.

Once the experimental period is ended, the task is to find the best data sets among those which were accumulated and then to find corroborative data from the other investigators which was taken at the same time and was focused on similar activity in the storm. For the TRIP data this can initially be determined on the basis of daily log sheets kept by the participants and by personal communications with the participants. However the usefulness of the actual data can only be determined after it is in hand. Hence on the preliminary appraisal of the Rice group's data, a best storm, that of July 22, 1977, was chosen as the focus of our attention. Enquiries were then sent to the other investigators asking for data from this day.

Bringing together the available data sets from this storm and displaying them in coherent fashion is a preliminary goal of this thesis. Next, establishing a context into which each of these different representations fits is outlined. Following this there is discussion of each observational technique, the explanation of the available data and its quality, and the methods used to bring the data to a presentable form.

In the chapter on discussion there are various schemes offered to juxtapose the variety of graphical data
representations available to us. Each attempt has as its purpose to depict the dynamics of the storm environment in relationship to the storm electrical activity. This thesis is unique then because of the emphasis on the synthesis and interpretation of the diverse data sets.

0.1. ORGANIZATION OF THESIS

In this introduction we have outlined the purpose and subject, both general and specific, of this thesis. Chapter 1 introduces the classical air-mass thunderstorm and sets the stage for the storm of interest in this thesis. In Chapter 2 the Thunderstorm Research International Program (TRIP) is explained and the participants in TRIP 77 and those who contributed resources to this report are introduced. Chapter 3 introduces the acoustic thunder ranging technique and the acoustic source location resources; Chapter 4, the Radio Frequency (RF) source location (LDAR) resources and data set. Chapter 5 describes a fast scanning meteorological cloud radar and the data set associated with it. Chapter 6 completes a summary of the other supplementary data available for the storm along with the available weather information for July 22, 1977.

Chapter 7 brings together the previously introduced data representations, compares, and interprets the various observations. It is here in this chapter that the gist of the thesis is presented. While storms have been analyzed
before, this paper is one of only a few that looks at this storm, and it is the only attempt to bring together so many data sets for a complete storm episode. In the context of the storm dynamics, various juxtapositions of the data are offered with the intent to elucidate the dynamical evolution as it relates to the electrical activity from the storm.

Conclusions are presented in Chapter 8 along with pertinent suggestions on the design considerations for future cooperative experimental programs studying the thunderstorm environment.

Appendices contain the bulk of the accumulated data and explanations of the radar data, the acoustic data, and the radio frequency ranging data. A list of participants in TRIP 77 who contributed data to this research but not mentioned in the body of the report is also included in the appendices.
CHAPTER 1

A THUNDERSTORM

1.0. THUNDERSTORMS

Meteorologists distinguish between two types of thunderstorms: the frontal storm and the air-mass storm. This distinction is based upon the environment and the mechanism which spawns the storm.

1.1. FRONTAL THUNDERSTORMS

Frontal storms as the name implies are associated with the large scale air movements caused by advancing fronts. These storms are most often associated with cold fronts, however warm fronts are also capable of spawning thunderstorms. Thunderstorms develop due to a cold front when a wedge of cold air pushes into and under a mass of warm air. If there is sufficient moisture in the lifted air then condensation is possible and large cumulus form as the air is lifted above the condensation level. If the warm air is unstable then cumulonimbus clouds develop and produce thunderstorms. Such circumstances can produce a line of thunderstorms for hundreds of miles along the advancing edge of a cold front. A particularly large member of this class is called the severe storm (e.g., Atkinson, 1981).
1.2. **AIR-MASS THUNDERSTORMS**

A thunderstorm which occurs entirely within one air mass unrelated to frontal effects is called an air-mass thunderstorm. This type of storm is driven by convection and fed energy via infusion of moist air.

In the case of the storms which form over the Florida peninsula in the summer there is no organized large scale frontal activity. There is a smaller scale diurnal effect called the seabreeze convergence line which is driven by the differential heating between the water and land. The effect of the seabreeze is to transport moisture inland during the day and to form a zone of convergence where the sea air meets the land air. Thus these conditions produce a local, heat driven thunderstorm; the seacoast thunderstorm; an air-mass thunderstorm.

1.3. **THE CLASSICAL AIR-MASS THUNDERSTORM**

The classical description of an air-mass thunderstorm was derived from an intensive field program known as the The Thunderstorm Project carried out in Florida and Ohio during the late 1940's. The schematic description of a "typical" cell shown in Figures 1.1 thru 1.3 is taken from this report [Byers et al, 1949].
Figure 1.1 depicts the cumulus stage of the development, which Byers [1949] describes as follows:

"... the thunderstorm cell has an initial diameter of 1 to 2 mi., and grows until its major axis is perhaps as great as 6 mi.... If the duration is reckoned from the time of initial detection of radar echo between 10 and 15 minutes...."

Figure 1.2 is an idealized cross section of the storm during the mature stage. Briefly, the mature stage is delineated by the onset of rain at the ground. The classical explanation [Byers, 1949] says:

"Duration. -- As the rainfall continues throughout the mature stage of the cell, the downdraft area increases in size until, in the lower levels, it extends over the entire storm cell. This is considered to be the end of the mature stage, which usually lasts for a period of 15 to 30 minutes."

The final stage is the dissipating stage. Figure 1.3 shows the criteria for assigning the beginning of this stage is the degeneration of the cloud into stratified layers. After Byers [1949]:

"In general, the however, period from the beginning of this stage until the time when vertical motion within the cloud becomes insignificant is approximately 30 minutes."

It is important here to note the time scale of the birth, evolution, and decay of such a "classical" thunderstorm description. Observations of the particular air-mass thunderstorm reported in this thesis will display markedly different time scales.
Figure 1.1 Cumulus stage of an air-mass thunderstorm
Figure 1.2 Mature stage of an air-mass thunderstorm
Figure 1.3 Dissipating stage of an air-mass thunderstorm
CHAPTER 2

THUNDERSTORM RESEARCH INTERNATIONAL PROGRAM TRIP-77

2.0. ORIGINS

Observing a thunderstorm is difficult because of its physical scale and the inherent unpredictability of weather. Solitary observations conducted without benefit of information from corroborating investigators tends to give an incomplete picture of the thunderstorm and its environment. Thus the need for cooperative studies such as the Thunderstorm Research International Program (TRIP).

The first TRIP was held in 1976 at Kennedy Space Center, and subsequent TRIP field studies were held in 1977 and 1978 at KSC, and at Langmuir Laboratory in Socorro, New Mexico in 1979 and 1981.

2.1. TRIP 77

The participants from Rice University Space Physics and Astronomy Department who conducted the experiments during TRIP 77 were: Dr. Arthur Few, Jerry Bohannon, Mike Stewart, Mark Weber, and Andy Weinheimer. Since the author of this thesis did not become affiliated with the Atmospheric Electricity group until late 1978 he did not participate in any of the TRIP programs held in Florida. Hence,
all the observations discussed here relative to the events in 1977 at KSC are dependent upon either the actual data sets or on conversations with the TRIP 77 participants. However, as regards the nature of such experiments the author was an active participant in TRIP 79 and TRIP 81 held at Langmuir Laboratory in Socorro, New Mexico and also in a cooperative experiment in central Oklahoma under the aegis of the National Severe Storms Laboratory during the spring of 1983.

A list of all the participants at TRIP 77 and their area of contribution is included in the appendix. Special mention is made here of the cooperation from Dr. Marx Brook who provided the fast scanning meteorological radar data ("REDBALL" Radar) data film and from Carl Lennon who provided the Lightning Detection And Ranging (LDAR) data tape. William Beasley was also very helpful in providing supplementary KSC data as was Richard Orville of State University of New York at Albany where much of the TRIP 77 data has been archived.

2.2. **DAY 77203**

The storm on Friday, July 22, 1977 (DAY 203), at Kennedy Space Center, (KSC) Cape Canaveral Air Force Station grew out of a typical midsummer weather pattern for the Florida peninsula. This storm was officially classed a "Significant data collection day (1977)" in the Report to
Management, TRIP - 77 [Taiani, 1977]; it was noted as having started at 1722 GMT and stopped at 1939 GMT; i.e., an "official" observational duration of 217 minutes. This figure is somewhat misleading since there was activity over a broad area during this day, hence it is reasonable to assume that this figure includes all activity within the range of observation stations at KSC on July 22, 1977. The particular storm of interest in this report had an observable lifetime, based on the high frequency RF activity (LDAR) and acoustic activity (THOR) recordings, of approximately 70 minutes.

A "Significant data collection day" is defined as one on which a storm occurred and more than one experimenter collected data on a that storm. This period is in the early afternoon hours of the diurnal cycle of convection. There were twenty (20) "Significant data collection days (1977)" during the period 17 June to 12 August, 1977. Several of these storms have previously been reported, [Lhermitte, Conte, Pasqualucci, Lennon, and Serafin, 1978; Lhermitte, 1978; Lhermitte and Krehbiel, 1979]. By early afternoon (18:35 GMT) a seabreeze convergence line had been established on a line parallel to the shores of the Banana and Indian Rivers. This storm occurred within the effective observing range of a variety of field observation networks established for the cooperative field program called TRIP 77; Thunderstorm Research International Program,
1977.

Relative to all the observations made by the Rice University group during TRIP 1977, this storm produced one of the better data sets. Relative to the entire TRIP 77 community of investigators it also represents a rich data set of very comprehensive thunderstorm observations. The effective observing period for the acoustic ranging network encompassed 18:05 GMT to 18:50 GMT. The other prime electrical data set for this storm, the RF ranging system (LDAR) covers the period 17:50 to 19:00 GMT.
CHAPTER 3

ACOUSTIC RESOURCES

3.0. BACKGROUND

During TRIP 77 a group from the Space Physics and Astronomy Department set out to make several types of measurements on active thunderstorms. One of the techniques was to record the acoustic energy, thunder, at the ground by using an array of microphones. The experiment will be referred to in this text as the THOR experiment in order to distinguish it from other observational techniques in the atmospheric research program at Rice University and from other investigations which were being conducted at KSC during the summer of 1977.

3.1. ACOUSTIC TECHNIQUE OBJECTIVES

The objectives of the Rice University team at TRIP 77 repeated here are taken from the Report to Management, Nov 1977, Attachment C1., [Taiani, 1977]:

"OBJECTIVES

a. Obtain data on the location and orientation of all major lightning channels both inside and outside the cloud throughout the time development of marine air-mass thunderstorms at KSC.

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b. Obtain data on the location and geometry of the charged cloud regions supplying charge to each lightning flash in the KSC thunderstorms studied.

c. Obtain data on nature and explanation of the infrasonic emissions from thunderclouds associated with electrical discharges.

d. Obtain vertical profiles of temperature and corona currents inside thunderclouds.

e. Correlate acoustic methods of lightning and source location with electromagnetic and multi-station electrostatic techniques.

f. Correlate electric fields inside thunderclouds with fields measured at the surface and on aircraft outside the thunderclouds.

g. Correlate regions of lightning activity and charge generation with thunderstorm dynamical data and with the thunderstorm microphysical data."

3.2. TRIP 77 ACOUSTIC EMPHASIS

The discussion which follows concentrates on objectives a., b., e., and facets of g., which address charge generation and dynamical data. The development applies specifically to the single thunderstorm which occurred within range of the Rice microphone arrays on the afternoon of July 22, 1977. The remainder of this chapter serves to introduce the acoustic experiment and outlines the manner
in which the data was acquired, reduced, and plotted.

It should be further noted that objectives d. and f. depended upon use of Balloon Electric Field Sensor (BEFS) and coronasonde (electric field measurement) balloon systems [Weber, et al., 1982, 1983]. However, restrictive administration proceedings prevented free balloon flights in the KSC air space and thus these objectives were abandoned during TRIP 77.

3.3. THUNDER RANGING

Thunder ranging using acoustic recordings of thunder has been used by various workers [Few, 1974; MacGorman, 1978; Uman et al., 1978; Bohannon, 1980] to map the locations of lightning channels in thunderstorms. Basically, the technique uses the differences between the time of the electric field change due to a lightning event and the arrival of a train of acoustic pulses measured at the ground by sensitive microphones. There are numerous embodiments and geometries possible when conducting such an experiment. During TRIP 77 the installation consisted of three arrays of four microphones each, distributed as shown in Figure 3.1.
Figure 3.1 Acoustic arrays as installed during TRIP 77
Such an arrangement when fully functional produces 12 channels of timing information. The time delays across an individual array are on the order of from several tens of milliseconds to several hundred milliseconds; whereas the delays between different arrays can be on the order of several seconds. Two methodologies are used to reconstruct the lightning channels using these data: thunder ranging uses the long arrival delays across any two of the arrays to determine locations of major features of a flash; ray tracing is a much more elaborate but more accurate method which cross-correlates the arrival delays across a single array. This latter technique also takes into consideration the atmosphere through which the acoustic wave propagates in more rigorous fashion. A replica of a typical oscillogram like those used in thunder ranging is shown in Figure 3.2. The same signal is simultaneously recorded on 1/2 inch magnetic tape using a novel analog/digital hybrid system encoded to 12 bit accuracy which incorporates a non-linear compression factor at the high amplitude end using FM format, hence achieving a substantially broader dynamic range than available with 12 bit resolution. Upon return from the experimental site these data tapes are decompressed and can then be "viewed" via a plot routine which provides for ad hoc selection of "chart rate" and peak amplitude scales. This step is preliminary to choosing which episodes are valid candidates for the subsequent
cross-correlation and ray tracing.

In order to extract source locations using ranging we must identify and then correlate the arrival of a given pulse or "clap" of thunder in common terminology at each of the arrays. Since we are dealing with times on the order of seconds (equivalent to millimeters on the oscillogram) it is possible to visually label related features (pulses) and to measure the offset between them; this then is thunder ranging process. A solution such as outlined in Few [1970] or Bohannon [1980] is used to map to a location in the cloud from which the acoustic energy emanates. This point of emanation is assumed to be a section of hot gaseous plasma associated with the lightning discharge.

Over the duration of a "flash" it can be seen in Figure 3.2 that there are several prominent, individually distinguishable pulses. Likewise, by "hand" correlating these prominent features, for a given flash, the locations of several major acoustic sources may be determined. This is a relatively straightforward, simple approach and is much quicker and less computationally intensive than the method of cross correlating the individual pulses in a given array [Few, 1970; Few and Teer, 1974; MacGorman et al., 1981] which is the basis of the process of ray tracing which gives many more locations which can then be reconstructed into a more detailed rendition of the channel.
Figure 3.2 Acoustic signature of a "flash"
3.4. CROSS CORRELATION - RAY TRACING

While the results are not reported here, much of the preliminary work leading to the cross-correlation solutions has been accomplished for the events mentioned in this discussion. The analog to digital tape format conversion and the high resolution plots of the microphone signal has been done for all the "thunder rangeable" events included in this discussion. What remains is to apply the cross-correlation routine to each of these events. Once the cross-correlations are in hand then the spatial coordinates for the correlated points (hot channel sections) in an event are available to reconstruct the channels using a ray-tracing routine [Teer, 1972]. The stumbling block to this last and most essential step has been the lack of sufficient computer capability. The calculation procedures necessary to produce these correlations are computation intensive and have always been the major bottleneck in bringing the data to a presentation and interpretation stage in a timely fashion. Even at the current levels of automation, circa 1979-1983, acoustic cross-correlations still require a significant level of human intervention in a slow and tedious process.

The full sequence of thunder ranging plots are included in Appendix B.
CHAPTER 4

REDBALL RADAR RESOURCES

4.0. REDBALL RADAR

The intent of this chapter is to introduce data from a fast scanning meteorological radar which was operated during TRIP 77 by a group from New Mexico Institute of Mining and Technology (NMIMT) lead by Dr. Marx Brook. A stated objective for this experiment during TRIP 77 as quoted from the TRIP 77 Report to the Management [Talani, 1977] was to

"b. Study of evolution of cloud reflectivity structure using a fast scanning X-band surveillance radar. Measurement of reflectivity intensification rates and the relationship between echo intensification and lightning occurrence, correlated with the raingage(sic) network measurements."

Brook has coined the label "REDBALL Radar" since the antenna is housed inside a distinctive red radome which spins on a horizontal gimbal which in turn rotates slowly in azimuth. These combined motions produce vertical cross-sectional scans of the cloud at the rate of 4 vertical scans per second with scanning plane sweeping in azimuth at 12 degrees.

A brief description of the fast scanning meteorological radar concept is given in Appendix D along with the
specific details of the implementation of the REDBALL radar.

4.1. REDBALL DATA

Data from the REDBALL radar operated in TRIP 1977 was available in the form of a 16 mm film of the radar scope. Dr. Brook provided an original negative from which a duplicate was printed. During the early part of the storm the camera was properly focused; however during the second half of the storm apparently the installation of a new film magazine caused the image to lose critical focus. Consequently, the latter half of the data is not in focus thus leading to more difficult interpretation.

Once the film was duplicated it was visually scanned using a 16 mm viewer; certain time sequences were then chosen for their pertinence to the other experimental data sets. Attempts were made to produce prints from the photographic enlargement of 16mm film frame. Some examples of these attempts are shown in Figures 4.1, 4.2, and 4.3. These figures represent overlays of REDBALL with ACOUSTIC (●) and LDAR locations (✓) centered about the time 18:35:02. These prints are now 3rd generation copies with yet another generation and consequent degradation in the photocopy final. Instead of proceeding with this photographic replication a more direct albeit tedious approach was chosen.
Figure 4.1 Enlargement of a REDBALL RADAR 16 mm film frame
18:35:00 to 18:35:02 Azimuth: 205.7° to 220.6°
Figure 4.2 Enlargement of a REDBALL RADAR 16 mm film frame
18:35:04 to 18:35:05 Azimuth: 241.5° to 256.8°
Figure 4.3 Enlargement of a REDBALL RADAR 16 mm film frame
18:35:02 to 18:35:04 Azimuth: 223.6 to 238.5
Using the 16 mm viewer, individual frames of interest are projected onto the viewer screen and were traced onto acetate cells preconfigured with the range circles. An example of this technique is shown in Figure 4.4. These are the REDBALL representation used in the remainder of this chapter. They render a more clear and more uniform picture than the example of a photocopy of the 3rd generation photographic specimen in Figures 4.1, 4.2, and 4.3. You will note that Figure 4.4 is the same sequence as the previous three figures but with a mirror reflection about the axis of the radar.

4.2. REDBALL vs ELECTRICAL ACTIVITY

Figure 4.5 depicts the evolution and collapse of a pair of turrets over the period of increasing electrical and acoustic activity and indicated on the time/activity histogram, Figure 4.6. The ten minute period starts at 18:20:21 and extends to 18:30:38 at the bottom of the figure. The columns represent three vertical slices of the cells; 235, 242 and 248 degrees, i.e., on a west-southwest line from the radar. The tops of these cells attain approximately 13 kilometers. Early in the sequence we see two distinct cells roughly 10 kilometers apart, after ten minutes these have grown together and the tops have collapsed.
Figure 4.5  Evolution and collapse of turrets on REDBALL Radar
Azimuth of 244 degrees; 18:28:35 to 18:49:05
4.2.1. **REDBALL: FIXED AZIMUTH; FIXED TIME**

Another manner in which to view the data is to consider a fixed azimuth and watch the development as a function of time. Figure 4.6 fixes the azimuth at 244 degrees and then shows the evolution of turrets over the period starting 18:28:35 to 18:49:05, a span of 21 minutes. During that time we see a complete evolution of a convective cell with growth from approximately 7 km to 15 km over a span of 10 minutes.

Now consider an approach to depict the evolution of the storm over its entire observable "life". Figure 4.6 is a histogram of the acoustic and RF activity with two periods highlighted by the elongated "zees" in the right margin; these indicate times where there is increased activity. Using these two periods to focus our interest, Figures 4.7 and 4.8 show the REDBALL scans during these times. Figure 4.7 covers ten minutes between 18:20 and 18:30, and Figure 4.8 covers the next minutes of activity, 18:32 to 18:42. Over both these periods there is fairly constant maximum cloud tops but there is indication of rapid evolution of the geometry of the tops themselves in the earlier sequence.
Figure 4.6 Histogram of electrical activity
Figure 4.8 18:32 - 18:42
The first sequence is culminated by the indication of the collapse of vertical growth and a subsequent decrease in the LDAR activity. In Figure 4.8 we are again looking in the same west-southwest direction, the sequence again shows another vertical growth stage culminating approximately 14 kilometers height at 18:40. Corresponding with this cloud growth there is an overall increase in the acoustic and LDAR activity. The peak of the activity is not as intense as in the earlier 10 minutes but there are more acoustic reports and the LDAR activity is more sustained. Unlike Figure 4.7, Figure 4.8 shows a single more massive cell with no companions in the vicinity.

4.2.2. CONSTANT QUADRANT AND CAPPIS

Figure 4.9 shows consecutive azimuthal sections looking 187 degrees to 271 degrees from the radar, the frames are approximately 6 degrees apart, roughly three frames per second. This sequence shows that there is a single cell in the southwest quadrant whose top is approximately 12-13 kilometers in height.

Using a similar technique of tracing the REDBALL contours from the screen of a 16 mm film viewer it was possible to synthesize Constant Altitude Plan Position Indication radar depictions from the REDBALL vertical hemispherical "slices." The locus of points defined by the joint intersection of the scan radial, the cloud return outline and
a constant altitude plane (in this case 5 kilometers was chosen) depicts the extent of the cloud at this altitude. Figures 4.10 thru 4.19 begin a series of combined fixed time REDBALL scans and the derived CAPPIs. In Figure 10 and subsequent CAPPIs the capital letters "A" denote the locations of acoustic sources occurring within 0.5 km of the 5 km altitude and during the period of the scans that comprise the CAPPI. The letters "T1", etc. denote the approximate locations of turrets projected onto the 5 km level.
Figure 4.10 REDBALL 5 km CAPPI; 1830 GMT
Figure 4.11 REDBALL 18:35
Figure 4.12 REDBALL 5 km CAPPI; 1835 GMT
Figure 4.13 REDBALL 18:32 - 18:42
Figure 4.15 REDBALL 18:45
Figure 4.18 REDBALL 5 km CAPPI; 18:50 GMT
Figure 4.19 REDBALL 5 km CAPPI; 18:55 GMT
CHAPTER 5

KENNEDY SPACE CENTER RESOURCES

5.1. RF LIGHTNING DIRECTION/RANGING

A major source of information on the lightning activity at Kennedy Space Center comes from the Lightning Detection and Ranging system (LDAR) introduced by Lennon (1975, 1976). The LDAR system consists of 5 to 7 stations. In the case of summer 1977 there were 7 stations, 5 of which are located at sites indicated in Figure 5.1. LDAR locates lightning events (RF sources) by measuring the time of arrival of radio frequency (RF) pulses at each of these seven sites. The locations of the signal sources are calculated using equations of three dimensional hyperbolic geometry [Lennon, private communication]. Only three remote and one central station are required for solution of the geometric problem; however the additional stations provide redundancy checks.

The system was designed to detect the log of the envelope of VHF radiation in the band 30 to 50 Mhz from atmospherics at all the stations and retransmit the information from each of the remote stations to the central station. A simple block diagram of LDAR implementation is shown in Figure 5.2. As indicated there are two data
branches: RESEARCH DATA and REAL TIME DATA. The data which we were supplied is the latter, there was no RESEARCH DATA recorded for the day July 22, 1977 [Beasley, private communication].
Figure 5.2  Block diagram of LDAR DATA Processing scheme.
An example of a detailed analysis of RESEARCH DATA is that of Rustan [1979] for several flashes from Florida storms in 1976 and 1977. Reduction of this type of data is compute intensive and usually a single flash can contain several hundred thousand sources. Rustan's analysis of the LDAR RESEARCH DATA has been criticized by Krehbiel, et al., [1984], because of the timing errors introduced in the data processing.

Rustan's technique provides source locations every 5 to 10 microseconds. Thus he determines about a factor of 500 times more locations than the original LDAR system in REAL TIME mode can accomplish.

The RESEARCH DATA is a high speed analog recording of the receivers. This tape is slowed down during playback and digitized. This resulting digital data theoretically contains all of the RF emissions detected in the receiver bandwidth.

In contrast, the REAL TIME DATA is analyzed output from a computer system dedicated to real time analysis of the receiver data. However, the REAL TIME DATA is computer limited and samples the RF emissions for 100 microseconds between computations. The dead time between samples is approximately 8 ms.

In addition to this data handling factor, our consideration of the data is further restricted by two sets of
conditions; one imposed by Lennon as indicated in TABLE 5.1
[Lennon, 1979, private communication]. The second restric-
tion was one that we imposed on the range of an acceptable
source location that it fall within the effective operating
range of the acoustic ranging system (THOR) of 20 kilome-
ters.

The major weakness in the geometric juxtapositions of
the available LDAR data and THOR data is that both
represent severely truncated statistical samples of a given
event. Moreover these two sensing techniques measure
phenomena of widely disparate scales. THOR locates large
scale hot channels whereas LDAR is capable of receiving
signatures of very large and also very small scale
discharge processes, also the range of LDAR is greater than
the effective range of THOR, thus the need for the initial
range truncation mentioned earlier.

5.2. LDAR DATA FOR DAY 7/20/83

Table 5.1 explains the format of the LDAR data which
was available for the storm. The 7 stations are analyzed
as two 4 station Y shaped arrays with the central station
in common. The X,Y,Z can be determined sequentially by the
two arrays as X1,Y1,Z1 and X2,Y2,Z2.
TABLE 5.1

DATA FORMAT

Basic matrix: \( M \) (100,18)

Where 100 is the number of data points stored per BLOCK and 28 is the floating-point word associated with each point as indicated in the following:

\[
\begin{align*}
M(n,1) &= \text{Ref. number. of .05 microsec. intervals to peak at local site.} \\
M(n,2) &= X1 \text{ coordinate in meters.} \\
M(n,3) &= Y1 \text{ coordinate in meters.} \\
M(n,4) &= (Z1*Z1) \text{ coordinate in meters squared.} \\
M(n,5) &= X2 \text{ coordinate in meters.} \\
M(n,6) &= Y2 \text{ coordinate in meters.} \\
M(n,7) &= (Z2*Z2) \text{ coordinate in meters squared.} \\
M(n,8) &= \text{Amplitude of site 0 LDAR and strike data.} \\
M(n,9) &= \text{Sync word, BLOCK number useful for catalog.} \\
M(n,10) &= \text{Day} \\
M(n,11) &= \text{Hour and Minute} \\
M(n,12) &= \text{Second and Millisecond} \\
M(n,13) &= \text{Delta T1 = (REF-W1) wideband.} \\
M(n,14) &= \text{Delta T3 = (REF-W2)} \\
M(n,15) &= \text{Delta T5 = (REF-W3)} \\
M(n,16) &= \text{Delta T2 = (REF-M1) microwave} \\
M(n,17) &= \text{Delta T4 = (REF-M2)} \\
M(n,18) &= \text{Delta T6 = (REF-M3)}
\end{align*}
\]

VALIDITY TESTS

Coordinates X1,X2 and Y1,Y2 within 10 meters to be valid. And Z1 and Z2 must be positive.

If the data pass the test, the coordinates are averaged: \( \text{i.e.,} \)

\[
X = (X1 + X2)/2 \quad Y = (Y1 + Y2)/2 \quad Z = (Z1 + Z2)/2
\]

This step serves to minimize system errors.

Acoustic ranging considerations imposes the restraint that only points within less than 20 kilometers be valid for consideration for later comparison to concurrent acous-
tic locations.

5.3. **LDAR DATA**

Figure 5.3 is an example of one mode of representing the output from the LDAR REAL TIME DATA display. It is shown here in the interest of completeness. Such a depiction is not very useful because the range scale is much too large in comparison to the other data renditions and the temporal "granularity" is too great; i.e., nine (9) minutes of activity is compressed into a single plot. This sample LDAR plot is the only one which was included with the LDAR data package which we received.

The two elevations to the left of the figure represent azimuthal projections of the two prominent groups of activity indicated in the plan view.

Figures 5.4 and 5.5 show the Range Error Circle for the LDAR system at ranges 5 miles (km), 10 km height, and 20 miles (3 km), 10 km height respectively. An aircraft was flown carrying a pulsed RF source operating within the LDAR receiver bandwidth. This source was located by the LDAR network and from knowledge of the aircraft position and the calculated LDAR locations these Range Error Circles were determined.
Figure 5.3 REAL TIME DATA display of the LDAR system
FIG. RANGE ERROR CIRCLE, 5 MILES

UNCERTAINTY IN RANGE AND IN HEIGHT
DUE TO QUANTIZING ERRORS OF 0.05
MICROSECONDS IN T1, T2, T3, AND T4

HEIGHT 10 KM, PRIMARY CONFIGURATION

Figure 5.4 Range error circle at 16 km; Height 10 km
Figure 5.5 Range error circle at 32 km; Height 10 km
CHAPTER 6

SUPPLEMENTARY DATA RESOURCES

6.1. KSC ELECTRIC FIELD METER DATA

The Kennedy Space Center (KSC) electric field meter network measures surface electric fields at each of 25 sites distributed over the Cape Canaveral Air Force Station. Surface equipotential gradient contours (EGC) are fit to the observed field measurements. This data set covers the period 07/22/77 1757:24.710 GMT to 1857:47.996 GMT. The spatial distribution of the network is shown in Figure 6.1 taken from the pamphlet KSC-DL-620 [KSC, 1977]. We were provided with paper copies of contour plots which occur at approximately 1 minute intervals. From these separate plots there have been reduced composite images made which depict approximately 5 minute periods per composite page. The data set is complete over the period 17:57.24 to 18:59.50 with two minutes of data missing between 18:05.36 and 18:14.50. However, the composites do not show the period 18:05.36 to 18:14.50 and the 15 minute period 18:45.31 to 18:14.38.

The interpretation of these drawings is based on the following explanation taken an excerpt from Kasemir (1978):
Figure 6.1 Map KSC Electric Field Mill network (KSC-EGC).
"KSC field contour maps

From measurements of 25 field mills scattered over an area of 18 x 27 km contour lines of equal gradient in steps of +1, +2, +3, ... kv/m have been calculated and are displayed on the KSC field contour maps. The polarity is indicated by a + or - sign inside the smallest gradient ring. Note that by atmospheric electric definition gradient and field have the same sign and by physical definition the opposite sign. The largest gradient ring has the absolute value of 1 kv/m and the values of successively smaller rings increase in steps of 1 kv/m if the noted scale is 1000. If the line scale is 100, the values are 100, 200, 300, ... v/m." [Kasemir, 1978].

6.2. KSC-EFM DATA FOR DAY 77203

Figures 6.2 through 6.9 show a montage of equipotential gradient contours, devoid of any other supplemental data. This sequence is composed of 45 time frames, each approximately one minute apart. Each figure spans approximately 5 to 8 minutes. The total time covered is one hour.

The early frames show a pattern of complex multiple charge distributions about a line roughly parallel and to the east of the shuttle landing runway. Figure 6.2 covers 8 minutes; it is a line scale 100 v/m. The next nine minutes are not shown but are in the data set. Figure 6.3 covers 1814.50 to 1819.55; it and subsequent figures are all at line scale 1000 v/m. Over this sequence there is little evolution.

Figure 6.4 begins to show the formation and migration of a pair of charge centers starting to the south of the
runway and separating along a line paralleling the runway.

Figure 6.5 depicts conditions from 30 to 35 minutes into the sequence. There is now a dissipation of the activity to the north of the shuttle runway and growth of both intensity and complexity to the south-southwest culminating on this figure with the complex multiple dipolar fields in the frame 1832.12. The next five minutes shown in Figure 6.6 indicate a relatively quiescent period in the storm; however the activity that exists is moving to the south. The next period in Figure 6.7 starts with high simple fields and then dissipates around 1844.29.

There is a gap of 7 minutes between Figure 6.7 and Figure 6.8; the latter shows the beginning of a new charge center just off the southern end of the shuttle runway. Figure 6.9 shows little change and ends the data sequence. Also by this time the main activity in the storm has dissipated. This data set is included in the interest of completeness much graphical manipulation remains in order to be able to interpret these contours in the context of the source location information and radar data. Not having available the raw digital format of these contours means that all of the scaling and origin rectification must be done by hand. However, here in this data we see a waxing and waning of the steepness of the gradients and complexity of the contours; this is consistent with the other indica-
tions of short term oscillations in intensity over periods on the order of 5 to 10 minutes.

In Figure 6.10 we have plotted the amplitude of the maximum measured field in each time frame. Features in this display mimic the other histographic depictions of activity, namely, the THOR/LDAR histogram and the LDAR raw data histogram. However, it is difficult to assert a correspondence or correlation because of the inherent granularities of these data sets. Nonetheless we see the trend of increasing maximum fields over the time span and there are dramatic swings similar to the features in the other manifestations of activity.
CHAPTER 7

SYNTHESIS AND DISCUSSION

7.1. LDAR & ACOUSTIC ACTIVITY

Having introduced the techniques employed at KSC during TRIP 77 we now bring together the graphical depictions of the various observations. The organizational backbone of this discussion is the histogram in Figure 7.1 showing the reconstructable THOR and LDAR sources as a function of time.

Figure 7.2 is a plot of raw LDAR activity versus time over the period 17:49 to 18:59 independent of the restriction on range or validity as outlined in the explanation of the LDAR data. From the activity profile of the storm we see that there were four or five periods of 5 to 10 minutes each when the intensity of the activity is very pronounced. While the early phases produced substantial electrical activity, as evidenced by the LDAR activity, the storm was still beyond the range of the acoustic arrays and hence there is limited information on acoustic source locations before the sequences at 18:35. An exception to this is seen in Figure 7.7 where two early isolated events at 17:58:54 and 18:06:00 are displayed in the context of the 18:35+ sequence.
Figure 7.1 Histogram of reconstructable LDAR and THOR sources
Figure 7.2 Raw LDAR activity from 17:49 to 18:59
Figure 7.1 and Figure 7.2 suggest that there are four episodes of intense RF activity; each episode approximately 5 to 10 minutes in duration with a period between intensity peaks of approximately 10 minutes.

The histogram in Figure 7.1 shows an anticorrelation between the inverted histograms near the end of the storm; from 18:35 to 18:50. This may suggest that following a major discharge the electric fields are locally reduced to below corona threshold potential resulting in a decrease of small scale RF activity. Between discharges, the cell regenerates strong electric fields which increases RF activity until another major breakdown occurs giving rise to a measurable acoustic event.

In previous studies [Teer and Few, 1974; Bohannon, 1978; MacGorman et al., 1981], representation of acoustic sources has been via the THOR "3 views" (three orthogonal projections) which were introduced in Chapter 3. While these represent a complete rendition of the thunder ranging reconstructable acoustic activity, they do not facilitate a clear exposition of the dynamics of the activity. In this development, we will introduce another scheme using closely related THOR plots to form a composite sequence of several flashes. These composites were derived from the corresponding THOR plots using the graphics capability of a stand-alone microcomputer, the Apple MacIntosh.
7.2. **ACOUSTIC SOURCE LOCATION COMPOSITES**

In Figures 7.3 through 7.10 there is a series of drawings for the sequence "18:35:00 - 18:35:16 - 18:35:39" showing their relationship in the cloud. This first sequence of three lightnings will be described in detail so that the reader will have an understanding of the methodology of forming the lightning-activity volume composites.

The lightning at 18:35:00 is shown as individual acoustic sources in Figure B.4. These points are all close together implying lightning activity occupying a volume containing the points. The lightning-activity volume is defined graphically by constructing a closed line in each of the three projections of the acoustic source points which encloses the points. The shaded volume shown in the three projections of Figure 7.3 was constructed from the points of Figure B.4. When points or groups of points are not close together on all three projections then disjoint closed lines are constructed. An example of disjoint lightning-activity volumes can be seen from a comparison of Figure B.20 with Figure 7.17.

Figure 7.3 displays the three lightnings occurring in the 39 second period listed above; the first event is shaded. Figure 7.4 is the same set of events; except here the first and second events are shaded. Figure 7.5 shows the three events without shading. While we see that there is
some overlapping of the regions penetrated by these three events, it is also evident that considered as an ensemble these separate events seem to be organized to penetrate disjoint volumes of the cloud. This suggests that the ensemble of flashes neutralizes a large volume of the charged region and after having done so, the storm requires some period to regenerate fields strong enough to produce the next period of intense activity.

In order to consolidate the active volume identified in these first three flashes for comparison with activity following and preceding the period, we form a composite volume, which contains all of the identified active volumes. Figure 7.8 is the composite volume formed from Figure 7.5. The two early lightnings at 17:58:54 and 18:06:00 are compared with the composite in Figure 7.7. Their separation in time and space indicates that they are unrelated to the activity in the 18:35:00+ composite. The lightning at 18:29:38 is depicted in Figure 7.6. This event occurs closer to the composite in both time and space, but it remains an isolated event and is not included in subsequent comparisons.

In the next sequence, "18:36:24 - 18:37:28 - 18:38:14 - 18:39:30," shown in Figures 7.10 thru 7.13, this spatial neutralization phenomena is again pronounced. Figure 7.14 is the composite volume of the four lightnings in this
three minute period. A peculiar feature in this sequence is the appearance of an avoided region: a vertical alcove-like volume from about 4 km up to about 10 km. Figure 7.9 compares the composite volume of these four lightnings with the earlier three. The relationship between the composites is similar to the relationships between the lightnings making up the composites. There is some overlap but the volumes are largely distinct.

The four lightnings, "18:40:42 - 18:41:10 - 18:41:36 - 18:42:18," are shown in Figure 7.15 as a composite; individual volumes are not displayed. The three lightnings, "18:42:59 - 18:43:39 - 18:44:21," are shown as a composite in Figure 7.16. An individual, "18:43:59," is also displayed on Figure 7.16.

The final three lightning events of the storm are shown as individuals in Figure 7.17. These active volumes are unusually long compared to earlier activity and they are widely spread and disjoint. It was not possible to form a composite with these three lightnings.

Figure 7.18 is an overlay of Figures 7.15 and 7.16. Again the discussion regarding adjacent volumes is applicable. Figure 7.19 is a supercomposite formed from Figure 7.18, which is then projected as an overlay on Figure 7.17. This allows us to compare the active volume of the eight lightnings between 18:40:42 and 18:44:21 with the final
three events. With the exception of part of one volume, the final three lightnings are exterior to the volume defined by the earlier activity. In several aspects these final three events are unlike the previous activity.
Figure 7.3

18:35:00

Figure 7.3 18:35:00
Figure 7.6

Shaded areas represent volume of acoustic sources for lightning flashes:

18:35:00
18:35:16
18:35:39

Figure 7.6 three+1
Figure 7.7

Shaded areas represent volume of acoustic sources for lightning flashes:
18:35:00
18:35:16
18:35:39
Figure 7.8

Shaded areas represent volume of acoustic sources for lightning flashes:
18:35:00
18:35:16
18:35:39
Figure 7.9

Figure 7.9 3+4
Figure 7.11

18:36:24

18:37:28

18:38:14

18:39:30
Figure 7.12

18:37:28
Figure 7.14 four
Figure 7.16 1843-4
Figure 7.17

1845-3

Figure 7.17 1845-3
CHAPTER 8

CONCLUSIONS

As a result of the juxtapositions of the various graphical data shown in Chapter 7 the following conclusions are suggested:

8.1. CLASSICAL DESCRIPTION DISCREPANCY

The airmass thunderstorm studied exhibits evolutionary changes on time scales and spatial scales that are significantly smaller than those described in text book examples: i.e., time scales less than or equal to 10 minutes rather than 30-60 minutes and areal scales of order 2-5 km rather than 6-10 km.

8.2. RF OBSERVATIONS VERSUS ACOUSTIC OBSERVATIONS

These thunderstorms produce copious quantities of RF radiation from small discharge processes that are not classically considered lightning (i.e., no flash of light followed by thunder). These high RF pulse rates can overrun the acquisition capacity of a system such as the LDAR and thus can lead to a skewed rendition of a discharge geometry for the overall event.

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These small discharges are concentrated in the upper part of rapidly-growing cold turrets (temperature less than \(-25^\circ\) Celsius). There is a prominent correlation in time and space between these dynamically and electrically active periods.

8.2.1. REAL TIME LDAR versus REAL ACTIVITY

Lightning detection and location systems that utilize RF technology detect a preponderance of information from small discharge events. During the inherent dead time of the detection process much information regarding the larger scale processes is lost to this technique.

Lightning detection and location systems which sample the RF data will produce biased information which emphasizes the smaller higher altitude sources.

8.3. ACOUSTIC OBSERVATIONS

Acoustic studies of lightning channels generally have shown that:

8.3.1. When compared with RF location data for the same phenomenon, good agreement is found in location. (Because of the RF sampling problem most RF locations do not correspond to the acoustic producing lightning phenomenon.)
8.3.2. Sequential lighting events occurring close together in time are related by having some portion of their space contiguous, yet most of the spaces occupy completely separate volumes.

8.3.3. When a set of sequential events are viewed the spaces of the lighting tend to fill a larger volume rather than repeatedly discharging the same volume. (This is important to considerations of thunderstorm charging rates because the lightnings are not discharging the same volume; hence, recharge between events are not necessary.)

8.4. SYNTHESIS OF OBSERVATIONS

Other conclusions from the synthetic interpretation:

8.4.1. Because of the observed spatial and temporal granularity in these data, both dynamically and electrically, conclusions regarding thunderstorm charging mechanisms based upon data lacking the requisite resolution will likely be flawed.

8.4.2. The testing of electrification hypotheses will necessarily require high time and space resolved data as well as in situ microphysical and electric data.

8.4.3. There appears to be a complementarity between the small upper cloud discharges and the lightnings in the sense that the small discharge rate decreases following the
larger lightnings.

8.5. SUMMATION

This thesis has shown that it is possible to bring together diverse observations of the thunderstorm environment into a comprehensible picture. The process can be tedious and is limited by the nature of the available data. Here we have attempted to show the entire active life cycle of a typical coastal air-mass thunderstorm storm which occurred during the summer of 1977 during TRIP 77 in Florida.

The variety and quantity of data presented here does not exhaust the amount that is available for the storm; however, it does represent a sample of each major experiment. Moreover the juxtapositions of the data offered in the earlier chapters only begins to exhaust the various possibilities.

Electrical activity as determined from the acoustic measurements (THOR) and RF measurements (LDAR) indicate that during the approximately 80 minute observation period there were prominent short periods of intense activity followed by lulls lasting comparable periods of time. This characteristic time period of this behavior was on the order of 5 to 10 minutes during the approximately 90 minutes of significant storm activity.
APPENDIX A

TRIP 77

This appendix presents information regarding the make-up of the cooperative atmospheric program Thunderstorm Research International Program (TRIP) 77. Included is a list of the principal investigators present at KSC during the summer of 1977 [Taiiani, 1977].

Of the various data sets available for the storm of interest on July 22, 1977, the graphic representation sets are the most easy to compare. However these offer the least spatial resolution. The resolution suffers because of the photographic process which is an inherent facet of the two radar data sets. In the case of the WSR-72X images and the 16 mm film from the Redball Radar the cameras were not properly focused on the radar scopes throughout the time of interest. In the case of the WSR-57x the film was poorly focused and improperly exposed leading to loss of definition of the precipitation contours. For the case of the LDAR data set, only the low time resolution analog version is available for the period covering this storm.

All the thunder ranging/LDAR plots are depicted in Appendix B. The overlaying of the THOR data and the LDAR is simple since these are both couched in Cartesian
coordinates, however the timing resolution is inadequate in the fact that in order to have some correspondence. Events from the two data sets are forced to relate even if they occur up to a minute apart. This is unphysical but it can depict the general level of activity in the cloud over periods which are short on the time scale of the dynamics of the storm cell(s) and can localize the region of activity over scales which are much smaller than the scale of the entire cell.

Correlation of the thunder sources from the thunder ranging data set with the Redball radar images does not suffer from the same concurrency problem since the radar depicts a slowly evolving geometry of the cloud and the cross-sectional slices come at regular intervals (see for example the CAPPIs in Chapter 4). However since we are provided with only a photographic blow up of a 16 mm motion picture film frame which is in marginal focus the definition of the boundary of the cloud is vague.
EXPERIMENTERS AND SCIENTIFIC OBJECTIVES

OBJECTIVES

a. Investigate various categories of thunderstorms in the vicinity of KSC utilizing an instrumented Learjet.

b. Conduct simulated lightning ground test utilizing the Learjet and electrostatic source provided by AFITL, Wright-Patterson AFB, Ohio.

c. Obtain magnetic field measurements of the nearby lightning environment from an airborne platform.

d. Obtain measurement of skin currents and induced transients within the aircraft while operating in a lightning environment.

e. Obtain a correlation between airborne and ground lightning test measurements.

f. Make electrostatic field mill measurements over the Cape Kennedy network for calibration of the ground network.

a. Location of lightning charge "centers" from time-resolved multistation electric field change measurements, and correlation of these results with storm physical structure as determined by multi-Doppler radar measurements of wind field, fast scanning radar measurements of cloud reflectivity, and in-cloud measurements of cloud microphysical and electrical structure. Also, correlation of the charge center results with the results obtained from LDVAR, the electric field mill network, and lightning channel reconstruction using thunder measurements.


c. Lightning fine structure measurements using a moving film lightning camera, and, as time permits, wideband electric field and radiation measurements.
EXPERIMENTER (CONT'D)

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OBJECTIVES (CONT'D)

2.

a. Obtain data on the location and orientation of all major lightning channels both inside and outside the cloud throughout the time development of marine air-mass thunderstorms at KSC.

b. Obtain data on the location and geometry of the charged cloud regions supplying charge to each lightning flash in the KSC thunderstorms studied.

c. Obtain data on nature and explanation of the infrasonic emissions from thunderclouds associated with electrical discharges.

d. Obtain vertical profiles of temperature and corona currents inside thunderclouds.

e. Correlate acoustic methods of lightning and source location with electromagnetic and multi-station electrostatic techniques.

f. Correlate electric fields inside thunderclouds with fields measured at the surface and on aircraft outside the thunderclouds.

g. Correlate regions of lightning activity and charge generation with thunderstorm dynamical data and with the thunderstorm microphysical data.

(See Marrero, P. J. for objectives).

3.

a. Using aircraft, determine the electric field and space charge distribution inside electrified convective clouds in the Florida area, and correlate the charge centers with meteorological parameters.

a. Study the overall evolution of lightning activity at the NASA Kennedy Space Center using the KSC field mill network and other sensors. The frequency of lightning discharges, the fraction of cloud-to-ground discharges, the fraction of discharges containing continuing currents, and the number of return strokes in cloud-to-ground discharges all will be measured as a function of time during summer storms.
b. Study the physical characteristics of lightning stepped-leader and return stroke currents using fast time-resolved measurements of the electric and magnetic fields produced by discharges at KSC. This experiment is part of a joint multi-station experiment with Dr. Martin A. Uman and his group at the University of Florida. Return stroke propagation speeds will be measured photoelectrically, and these speeds will be used to test models of how return stroke currents propagate up the leader channels.

c. Study sources of atmospheric radio noise in the HF and VHF bands using time-resolved electric field measurements with correlated sferics records.

a. LDAR, a Lightning Detection and Ranging System, will be operated at KSC. The space-time history of the lightning discharge process will be mapped by measuring the time of arrival (at 6 receiving stations) of lightning produced RF pulses in the 30 to 50 MHz frequency range.

1. To locate electrically active areas of a cloud and map the space-time history of the electrical discharges.

2. To determine the physical relationship between electrically active areas and rain areas of a cloud.

3. To detect and locate lightning strikes to ground.

4. To gather additional evidence that the observation that VHF radiation ceases just prior to the step leader making contact with the ground and resumes after the return stroke has been established.

5. To map lightning ground strike locations relative to electrical active portion of the cloud.

a. The general purpose of this research program is to examine the structure of waveforms radiated from lightning for characteristics which are indicative of storm type. In particular, to determine whether or not tornado bearing storms can be identified on the basis of the RF radiation associated with the storm system.

b. The specific objective at KSC will be to collect waveforms at frequencies from HF-VHF in conjunction with other monitoring of the lightning in order to associate the RF structure of the lightning with physical parameters of the lightning flash and with the dynamics of the storm.
EXPERIMENTER (CONT'D)

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OBJECTIVES (CONT'D)

a. Study of the three dimensional structure of motion and radar reflectivity fields inside thunderstorms. Special attention will be given (but not limited to) the study of strong updraft or downdraft observed by the system inside convective storms as related to the distribution and evolution of electric charges in the storms, or the occurrence of lightning, which will be observed.

a. Flight evaluation of a lightning detector instrument package (Stormscope). Test bed will be a T-39-B aircraft equipped with a new digital weather radar (Rendix RDR-1300) and transient digitizer system (WF-2222) for evaluation of the Stormscope.

b. A ground station will evaluate a newly developed narrowband UV optical densitometer system & ground testing of optical charges in air density (wind) and/or rainfall as a function of lightning activity.

c. Laser triggering of natural lightning using a high peak power laser (4x10^8 watts) and suitable optics for triggering and/or providing a convenient path for lightning discharge.

a. Utilize a Pulsed Laser Doppler System to prove the feasibility to measure the gust from velocities in the non-precipitous regions of a storm and measure the associated wind shears. The goal is to collect data on the penetration of the CO2 laser beam into the storm and compare this data with standard wind anemometers on a tower, weather and doppler radars.


b. Study of relations and differences between electric fields at the earth's surface with those within active thunderclouds.

c. Study of precipitation formation and development in Floridian thunderclouds with special attention given to the precipitation in warm regions of the cloud.

d. Determination of charge and electric field distributions aloft in developing Floridian thunderclouds.

e. Cooperative study of relations between rainfall and lightning over KSC.
EXPERIMENTER (CONT'D)

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OBJECTIVES (CONT'D)

See Arabian for objectives.

a.

Measure the return stroke velocities near the ground and simultaneously
record the electric and magnetic fields (Uman, Drider). From these data
it may be possible to calculate the electric current flowing in cloud-to-
ground return strokes in the first few tens of microseconds.

a. Evaluate WINDS data to compute patterns of divergence and convergence and
compare the strength of these fields with lightning frequency. The hypothesis is that strength of convergency is a measure of thunderstorm
activity.

See Lennon for objectives.

a. An S-band radiometer will be used on a narrow-beam, steerable antenna to
measure the radiation from clouds and thunderstorms. The major objectives of this program is to ascertain whether the presence of cloud electrification can be detected in this way. If this is possible, an attempt will be made by collaborating with other investigators to determine those electrical processes or conditions that resulted in remote detection. Of particular interest are electric fields at the ground and aloft, precipitation and
lightning. In addition, the radiometric data will be correlated with radar
data.

See Stubbs for objectives.
EXPERIMENTER (CONT'D)

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OBJECTIVES (CONT'D)

a. Lightning Triggering at KSC: The basic rationale for triggering lightning at the John F. Kennedy Space Center (KSC) is to control lightning and increase the number of strokes to a structure in a known time frame to quickly verify the lightning protection of the structure and associated ground support equipment (GSE) with natural lightning. In addition, natural lightning currents could be used to verify the lightning protection of flight hardware and other components, and even full-scale aerospace vehicles. Natural lightning possesses high voltage and energies not available from simulators, and this makes it very useful for final verification testing of the lightning protection of large structures, or components that include composite materials.

b. Field measurements of the spacetime history of intracloud discharges superimposed on Doppler radar motion fields and precipitation structure.

c. Contribute to knowledge of physical processes acting in charge separation and discharge.

1. To measure indirectly time-dependent optical transmission properties of clouds using two ground stations, separated by one km.

2. Basic objective is to measure return-stroke current waveshapes by operating fast electric and magnetic field antennas at KSC and Gainesville.

b. Operation of two TV systems to accumulate information on Lightning location, time of occurrence, strokes per flash, etc.
APPENDIX B

THOR RESOURCES

APPENDIX B THOR RESOURCES

This appendix contains the plots of thunder events which were able to be "thunder ranged." Table B.1 lists the prominent events from the oscillographic record from July 22, 1977. Included in this tabulation are the number of locatable points in the time frame for both the thunder record and the 4 second LDAR sampling bin centered on the electric field change signature. The last column indicates that on first perusal of the oscillograph not every event produced rangeable locations.

Twenty plots are presented which cover the acoustically observable lifetime of this storm. The plot format consists of one plan view with the origin of the microphone Array #2 at (0.00,0.00), and two orthogonal elevation plots. A thunder source location is depicted by a (+) and where available, a LDAR source location by a (x). In order to facilitate uniform plotting scales the origin on the frame moves from event to event to accommodate the range of the activity so that the display is maintained as close to the center of the plan view as is practical.
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<th># LDAR pts.</th>
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<td>-</td>
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</tr>
<tr>
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<td>-</td>
<td>-</td>
<td>TR/ LDAR</td>
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<td>10</td>
<td>TR/ LDAR</td>
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**TABLE APPENDIX.B.1**
Figure B.8
Figure B.18
Figure B.19
Figure B.21
APPENDIX C

KENNEDY SPACE CENTER RESOURCES

C.1 SUMMARY OF WEATHER

The following was prepared by Russell Stark on the staff of NOAA Weather Service Office at NASA/KSC and is quoted verbatim:

"Summary of Weather: Friday 22 July 1977 (77203)

A surface high ridge was just south of KSC while the upper air ridge was still north of us. The 0905Z sounding showed west winds below 3K ft. veering quickly to NNE at 7K ft., becoming ENE at 19K ft., then briefly north at 26K ft., then back to ENE above 29K ft. Speeds were calm at the surface, 10 kts at 1 and 2K ft, then decreased to 5 kts at 15K ft. increasing slowly to 35 kts at 48K ft. Moisture was high only to 7K ft and then the atmosphere was very dry to 25K ft.

Small Cu(mulus) didn't form until 1030 EDT (1430Z(GMT)). At 1235 EDT (1635Z) cells began to appear on the WSR-72X radar and by 1320 (1720Z) showers were visible to the NW and SW. These cells were along the seabreeze convergence front. By 1338 EDT (1738Z) the LDAR was recording beeps(sic) 10-15 miles to the NW and 17 miles to the SW at the 25K ft level.
Some cloud-to-ground flashes were seen to the distant NW from a 37K top. Soon after the western field mills (7 and 18) began showing negative readings. Thunder was heard from a cloud-to-ground flash to our west, 33 seconds to thunder. The thunderstorm was expanding eastward but radar indicated movement to the south. Rain fell briefly at the MSOB (Meteorological Service Office Building) at 1456 EDT (1856Z,) and the thunderstorm then rapidly dissipated.

LDAR indicated a shift to the south about 16 miles from the radar. A fire was started by lightning west of the shuttle runway approximately at 1440 EDT (1840Z). Later in the day this fire grew and a cumulus developed with a top reaching 7K ft. The 0905Z sounding showed a K index of 21.8; Lifted Index of -1.8. Neumann Thunderstorm probability was 27%.

C.2 NWSR-72x RADAR SAMPLES FROM JULY 22, 1977.

Included here are examples of some National Weather Service -72x radar images. We have a 35 mm film duplicate of the Plan Position Indicator (PPI) radar scope which covers the majority of the storm period. This data is very "granular" in the sense that there are significant lapses in the time sequence and also the range was changed from time to time during the period with the result that our storm of interest was not always scanned at the most advantageous working range. Again, as with the REDBALL radar
film, there are some sections which are not in critical focus and much of the time the supplemental indicators are difficult to decipher.

C.3 WSR-72 SUMMARY

Significant radar observations, WSR-72X:

<table>
<thead>
<tr>
<th>Time (GMT,Z)</th>
<th>Height (K ft.)</th>
<th>Azimuth (degrees)</th>
<th>Range (K ft)</th>
<th>Intensity (dBZ)</th>
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<td>(km)</td>
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<td>(km)</td>
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</tbody>
</table>

Russell T. Stark III
C.4 FIELD MILL SUMMARY

Initial activity: 1800Z, FM #7, 10, 18
First -3 KV/M reading: 1811Z, FM 7
Maximum background field: -6 KV/M, FM 22, 1852Z
-2.6 KV/M, FM 17, 1843Z
Maximum reversal: 6 KV/M, FM 22, 1848Z
-4.2 KV/M, FM 22, 1828Z
End time: 1930Z, FM 22
Between 0100 and 0200Z some coastal and southern field mills had slight negative readings.
Trace of rain at MSOB, 1546 EDT (1846Z.)
Wind direction reversal at MSOB but no strong gusts.
Adverse warning issued valid 1430-1530 EDT;
cancelled at 1510 EDT.
The table below contains data from the RAMS (Rapid Atmospheric Movement System) sounding taken on the morning of 22 July 1977 at 0905 Z (0505 EDT).

<table>
<thead>
<tr>
<th>Time (Z)</th>
<th>Temp (°C)</th>
<th>RH (%)</th>
<th>Wind (knots)</th>
<th>Wind Direction</th>
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**Surface Data:**
- Pressure: 1013 hPa
- Dew Point: 10°C
- Wind Speed: 15 knots
- Wind Direction: 090°

**Atmospheric Data:**
- Temperature: 22°C
- Humidity: 75%
Tabulated data from RAWINSONDE atmospheric sounding taken the morning of 22 July 1977 at 0905 Z (0505 EDT).
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RAWinsonde sounding reduced to mandatory levels

Sounding taken at 0905 Z [0505 EDT].
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Rawinsonde sounding taken at 0905 Z.
D.1 THE REDBALL RADAR

A detailed examination of the radar echoes produced by precipitation shows rapid fluctuations of the signal strength. It changes from pulse to pulse even when successive pulses are only a thousandth of a second apart. These fluctuations are caused by movement with respect to one another of randomly distributed particles within the scattering volume being illuminated by the radar beam. As the particles move, the phases of the individual backscattered signals change and the summation of the signals changes from one pulse to the next.

A target composed of distributed targets which move with respect to one another is said to be incoherent.

A target which is a single solid object, such as a metal sphere, or corner reflector, or an airplane, is said to be a coherent target.

In the general radar equation, we consider the average back scattered power, $P_r(\text{avg})$. Only if this quantity is measured correctly will it be proportional to the sum of the backscattering cross sections of all the particles in the illuminated volume.
At any given time, angle, or range the backscattered power from a specific scattering volume depends not only on the backscattering cross sections of the particles but also on their relative positions.

Thus the pulse to pulse fluctuation of the video signal from a radar receiver is caused by the random fluctuations of the individual scatterers in the volume of the cloud being sampled. These fluctuations are a fundamental property of meteorological radar returns. Their presence is a limitation on the sampling accuracy and reflectivity; however, it provides a mechanism to yield turbulence information regarding the scattering volume.

Following Battan (1973) we use TTI as the time to independence; it is the measure of the time required for the correlation between the amplitude of the video signal at time \( t + TTI \) to be independent of the signal amplitude at time \( t \).

TTI is a significant limiting factor in several radar meteorology determinations. It sets the lower limits on sampling times for noncoherent position/reflectivity systems and by the same token, sets limits on the range/velocity ratio in the case of coherent Doppler systems. For instance, knowing the the time required for independence one can satisfactorily specify the averaging time needed to obtain an adequate measure of \( Pr(\text{avg}) \) when
the radar is viewing the same scattering volume. It should be at least 10 TTI which at the 10 cm wavelength is at least 300 milliseconds and at 3.2 cm wavelength is 90 milliseconds.

A detailed discussion on time, angle, and range averaging of radar echoes from distributed targets is given in Walker et al., (1980). The constraints placed on the system by such considerations above are not a problem for normal meteorological sampling rates; however, in the case of a cloud physics or microphysics investigation, there are large volumes in space which must be sampled accurately on the time scale of convective motions in the cloud.

The statistical sampling time criteria requires sampling times sufficient to reduce the variation in the measured reflectivity so that a true representation of the backscattering cross section of the volume may be determined. These constraints when applied to a real radar problem can result in times to scan the entire overhead hemisphere on the order of several to 15 minutes in some cases. Such times are too long compared with the convective time scales in the cloud.

D.2 REDBALL RADAR; A Fast Scanning Meteorological Radar

In order to circumvent these time-to-sample problems and still obtain accurate measures of the average reflectivity, Dr. Marx Brook at New Mexico Institute of Mining
and Technology has formulated a technique to rapidly scan the overhead hemisphere. His technique averages the sampled volume by varying the frequency of the radar as it illuminates the scattering volume. Instrumentally, this is achieved by the use of the random frequency variation inherent in a band of noise 40 megaHertz wide centered at the wavelength of a 3 cm radar (10 gigaHertz).

The feature of importance in this technique is the behavior of the square detector in detecting a noisy signal. The fact that this behavior gives a well defined measure for the variance of the mean power returned is the crux of the system's.
D.3 SPECIFICATIONS OF REDBALL RADAR DURING TRIP 77

Specifications of the REDBALL radar as installed by the group at New Mexico Institute of Mining and Technology during the cooperative TRIP-77 are given below:

Center frequency: 10 gigaHertz
                 (3 cm wavelength)

Noise pulse width: 40 megaHertz

Peak power: 65 kilowatt

Pulse Rep. Frequency (PRF): 4 kilohertz

Theoretical maximum range: 37 kilometers

Extent of sampled volume: 45 meters

Beam width: 3 degrees

Mechanical rotation rates:
  (azimuthal axis) 2 revolutions/minute
  (12 degrees/second)
  (horizontal axis) 4 revolutions/second

Time to scan entire hemisphere: 15 seconds.

Display format: semicircular; (Vertical Height Indicator) range rings every 5 kilometers

Data resource: 16 mm b/w workprint
Blow-up of WSR-57 data from 35 mm film.
Reflectivity recreations from original WSR-57 data film.
REFERENCES


Taiani, A. J., Thunderstorm Research International Program TRIP 77, Report to management, TR 1556, Kennedy Space Center, 1977


