

1995 NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM
JOHN F. KENNEDY SPACE CENTER
UNIVERSITY OF CENTRAL FLORIDA

57-47

7747

1.30

LIGHTNING FORECASTING STUDIES USING LDAR, LLP, FIELD MILL,
SURFACE MESONET, AND DOPPLER RADAR DATA

Dr. Gregory S. Forbes, Associate Professor
Mr. Steven G. Hoffert, Graduate Student
Department of Meteorology
The Pennsylvania State University
University Park, Pennsylvania

KSC Colleague - Carl Lennon
Atmospheric Science

Contract Number NASA-NGT-60002
Supplement 19

August 8, 1995

ACKNOWLEDGEMENTS

Participation in the NASA/ASEE Summer Faculty Fellowship Program has been an enjoyable and professionally stimulating experience. Appreciation is extended to all those who support this program financially, and to the many individuals who made presentations or gave tours to the Faculty Fellows. Particular thanks are extended to Dr. Ray Hosler, Co-Director of the NASA/ASEE Summer Faculty Fellowship Program, and to Kari L. Stiles, Administrative Assistant, who coordinated the program extremely well.

It was a great pleasure to work with Carl Lemmon and others associated with the Lightning Detection and Ranging (LDAR) system in TE-1SD. Carl Lemmon is to be congratulated for the development of the LDAR system, which shows great capabilities in revealing the presence of electrical discharges within, and emanating from, thunderstorms. His support and encouragement of the applied research reported here is appreciated. The authors benefitted from discussions with Launa Maier, who has vast knowledge of thunderstorms and their electrical processes.

The authors are very appreciative of the efforts of the NYMA employees, Steve Schaefer and Phil Gardner, who operate the LDAR system and archive its data, and patiently dealt with many data requests and the increased computer load while the data were being processed. They, together with TE-1SD, made computer resources available for LDAR data processing. Steve was particularly helpful in retrieving data for the studies described below.

Many groups and individuals helped provide companion data sets for use in the study. Bart Hagemeyer (MIC) and Dave Sharp (SOO) all of the National Weather Service Office in Melbourne, assisted in WSR-88D radar data acquisition. Phil Gemmer of EG&G and Hal Herring, Susan DeRussey and Val Valek of CSR provided field mill and wind tower (surface mesonet) data. Gerry Talley of TE-COM-2 provided LLP data. John Manobianco and Mark Wheeler of the Applied Meteorology Unit (AMU; ENSCO) are helping acquire wind tower data.

Graduate student Steven G. Hoffert of Penn State participated in the summer research project. He took the lead in radar data retrieval and overlaying LDAR and other data on the radar imagery and was liaison with the National Weather Service Office in Melbourne in their process of learning to use LDAR data in operational weather forecasting. Over the past year he and Matt Pearce, another Penn State graduate student, developed the radar and overlay display software used in the research. John Madura of the Weather Projects Office (TM-SPO-3) provided financial support for the participation of Steve Hoffert.

The processing of large quantities of data from diverse sources required considerable computer support. Phil Gemmer, Lloyd Albright, Mark Sorger, Carol Lundberg, and Cheryl Axelson of EG&G provided exceptional service in loading data onto the KSC computer system (KSDN). Carl Lemmon of TE-1SD made a workstation available to Steve Hoffert. John Kiriazes and Steve Tam of TE-COM helped provide access to the Internet, and helped with other computer problems. John Diercks and Art Person of Penn State provided computer assistance via phone and e-mail. Workstations in the Wave Analysis Lab were used to display radar data and LDAR overlays, and the assistance of Tom Henning (NGTS) is appreciated.

The authors look forward to a continued interaction with Carl Lemmon, Launa Maier, Steve Schaefer, Phil Gardner, and others using LDAR data for weather applications, including Robin Schumann (ENSCO) and Frank Merceret of the AMU/TM-SPO. Our goal is to help the operational weather forecasters of the 45th Weather Squadron--detached out of Patrick AFB, USAF Space Command--who provide KSC with operational weather support from the Cape Canaveral Forecast Facility.

ABSTRACT

The ultimate goal of this research is to develop rules, algorithms, display software, and training materials that can be used by the operational forecasters who issue weather advisories for daily ground operations and launches by NASA and the United States Air Force to improve real-time forecasts of lightning. Doppler radar, Lightning Detection and Ranging (LDAR), Lightning Location and Protection (LLP), field mill (Launch Pad Lightning Warning System--LPLWS), wind tower (surface mesonet) and additional data sets have been utilized in 10 case studies of thunderstorms in the vicinity of KSC during the summers of 1994 and 1995. These case studies reveal many intriguing aspects of cloud-to-ground, cloud-to-cloud, in-cloud, and cloud-to-air lightning discharges in relation to radar thunderstorm structure and evolution. They also enable the formulation of some preliminary working rules of potential use in the forecasting of initial and final ground strike threat. In addition, LDAR and LLP data sets from 1993 have been used to quantify the lightning threat relative to the center and edges of LDAR discharge patterns.

Software has been written to overlay and display the various data sets as color imagery. However, human intervention is required to configure the data sets for proper intercomparison. Future efforts will involve additional software development to automate the data set intercomparisons, to display multiple overlay combinations in a windows format, and to allow for animation of the imagery. The software package will then be used as a tool to examine more fully the current cases and to explore additional cases in a timely manner. This will enable the formulation of more general and reliable forecasting guidelines and rules.

SUMMARY

A diversity of data types have been used to seek to augment the meteorological bases upon which lightning forecasts are issued. The goal of this research is to develop rules, algorithms, display software, and training materials that can be used to improve the real-time lightning advisories issued for daily ground operations and launches by NASA and the United States Air Force (USAF).

Research during 1995 built upon studies conducted during the previous two years. Over that period we sequentially developed capabilities to use Lightning Detection and Ranging (LDAR) data in conjunction with Lightning Location and Protection (LLP), Doppler radar, sounding, wind tower (surface mesonet), wind profiler, and field mill (Launch Pad Lightning Warning System--LPLWS) data. Beginning in summer, 1994, we developed computer software to overlay these data sets and display them as color images. In summer, 1995, we used these tools to pursue a number of case studies aimed at providing insight toward the solution of several lightning forecasting challenges.

One of the key lightning forecasting challenges is to anticipate where and when lightning will appear in the vicinity of the NASA and USAF warning sites. Surface mesonet data can provide useful information by highlighting regions of convergence of the wind, where dynamic forcing can augment the buoyant process of thunderstorm formation. This type of forcing is most effective when the convergent location is collocated with a local temperature (buoyancy) maximum. The convergence can be a result of the sea breeze front, the outflow from some previous or nearby convective storm, or other phenomena. We have found that mappings of the temperature and wind vector change over short (15 to 30-minute) time intervals can highlight areas where local hot spots are forming and where the air is becoming more convergent. Radar and satellite can also show the location where clouds are growing largest and tallest. We have found that once the radar reflectivity of the storms reaches 30 dBZ at or above the 8 km level, then the development of lightning can be expected if the storm remains active. The existence of storm-top divergence using Doppler radar signifies that the storm continues to have updraft and should proceed to generate lightning.

Another key lightning forecasting challenge is to determine when the threat of cloud-to-ground lightning has ended. In many situations anvil and other cloud debris--generated within convective towers and then either carried downwind of slow-moving storms or left behind by storms moving faster than the winds aloft--remains electrically active for tens of minutes to hours over points where the ground strike threat has not yet begun or has long ago ended, respectively. These clouds can be affiliated with large surface electric fields and with numerous discharges aloft detected by LDAR. This research seeks ways to identify where and when the threat of ground strikes is sufficiently small that phase 2 lightning advisories are not needed. Our studies to date indicate that ground strikes are rare beyond regions where the 20 dBZ reflectivity contour reaches the ground, even if there is higher reflectivity aloft. However, there are notable exceptions. Also, lightning activity may cease once no portion of the storm or adjacent storm has reflectivity of more than 30 dBZ above about 7 km. Adjacent storms must be monitored because cloud-to-cloud discharges initiated in the elevated regions of active storms apparently travel along the anvil or other cloud layers to impact weaker cells nearby.

A third key lightning forecasting challenge is to know where and when ground strikes occur within active convective storms. How far beyond the edge of the current LDAR discharge pattern, or radar echo, or cloud does there remain a non-negligible threat of an imminent ground strike? This topic is also addressed. Probabilities of ground strikes per square kilometer per minute are computed as a function of radius from the center of the composite LDAR discharge pattern. In most cases, ground strikes do not occur more than about 2 km beyond the edge of where the 20 dBZ reflectivity contour lies in the lowest 4 km.

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
I	INTRODUCTION	7
1.1	Data Sets Used in the Research	7
1.2	Past Results and Current Objectives	8
1.3	Use of Multiple Data Sets in Lightning Forecasting	8
II	GROUND STRIKE PROBABILITY IN RELATION TO LDAR PATTERN AND RADAR ECHO	10
III	JOINT USE OF METEOROLOGICAL DATA SETS IN FORECASTING INITIAL LIGHTNING THREAT	13
IV	JOINT USE OF METEOROLOGICAL DATA SETS IN FORECASTING TERMINATION OF LIGHTNING THREAT	19
V	CONCLUDING REMARKS	29
	REFERENCES	30

LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Title</u>	<u>Page</u>
2-1	Probability of a lightning ground strike within one minute	10
2-2	Examples of ground strikes in low-reflectivity regions	11
3-1	Surface mesonet data from 1650 UTC on 18 July 1994	14
3-2	Streamlines and divergence of the surface wind at 1650 UTC	15
3-3	Radar depiction of the initial storm development	16
3-4	Doppler velocities in the storm of Fig. 3-3	17
3-5	Radar and LDAR depiction of the storm from 1709-1714 UTC	18
3-6	Radar and LDAR depiction of the storm from 1715-1721 UTC	20
3-7	Doppler velocities in the storm of Fig. 3-6	21
3-8	Radar depiction of the post-threat storm on 19 July 1994	22
3-9	Radar and LDAR depiction of the post-threat storm on 12 June 1995	23
3-10	Radar and field mill data corresponding to Fig. 3-9	24
3-11	Radar and LDAR depiction of quasi-horizontal lightning layers	26
3-12	Radar and LDAR depiction of this case, including a ground strike	27
3-13	Radar and field mill depiction of the storm at a later stage	28

I. INTRODUCTION

The Kennedy Space Center (KSC) is located in one of the regions of the United States (and even the world) that encounters the most lightning strikes to ground per unit area (refs. 1,2,3). The possibility of lightning at the surface or aloft is, of course, a hazard that must be avoided during launches. On a daily basis, however, there are many operations at KSC which must be curtailed if there is a threat of a lightning strike to ground in the vicinity. The accuracy and timeliness of lightning advisories, therefore, has both safety and economic implications. The ultimate goal of the research described in this report is to provide information that can be used to improve the process of real-time detection and warning of lightning by weather forecasters who issue lightning advisories.

1.1 DATA SETS USED IN THE RESEARCH

Special networks of remote sensing equipment have been established to provide highly accurate information concerning lightning in the vicinity of KSC: the Lightning Location and Protection (LLP) system, the Lightning Detection and Ranging (LDAR) system, and a Launch Pad Lightning Warning System (LPLWS). In addition, a Catenary Wire Lightning Instrumentation System (CWLIS) detects electrical surges in wires at the launch pads when struck by lightning. The first two systems detect lightning signatures. LPLWS, by contrast, responds not only to lightning but also detects electric fields at the surface induced by electrified clouds, thunderstorms, and other atmospheric conditions. Data from the LLP, LPLWS, and LDAR systems were used in this study.

The LLP system (ref 4) detects lightning ground strikes through use of a network of magnetic direction finding antennae which sense electromagnetic disturbances triggered by lightning in a broad band of frequencies. Individual antennae detect a particular ground strike at different azimuth angles, and the location of the ground strike is essentially determined by finding the point of intersection of lines drawn from the antennae toward the source of the disturbance. The LLP system is approximately 90% efficient in detecting ground strikes near KSC, with position accuracy of about 1 km.

The LDAR system was developed by Carl Lennon and colleagues at KSC TE-CID-3 (ref 5). Its antennae detect lightning-induced disturbances at 66 MHz (VHF) frequency of the stepped-leader type. This system uses a time of arrival (TOA) approach, and achieves extremely accurate timing through use of the Global Positioning System (GPS). The lightning-induced disturbance, travelling at the speed of electromagnetic propagation, arrives at different antennae at slightly different times. The three-dimensional position of the lightning source is determined by essentially converting these time offsets into distance differences, and then performing a triangulation. The LDAR system began real-time operation in June, 1992.

The LDAR system can generate up to 10,000 data points per second, yielding numerous data points per lightning flash. Tests of the position accuracy of the LDAR data by Launa Maier have shown that within 10 km of the central antenna, 95% of the data points are accurate to better than 200m, and 50% are accurate to better than 100m.

Companion data sets included Doppler radar data from the National Weather Service WSR-88D at Melbourne, Florida, wind tower (surface mesonet) data, and rawinsonde data from Cape Canaveral. Future research will include the use of data from the National Center for Atmospheric Research CP-2 multiparameter radar that operated from 3 July through 17 August 1995. This dual-wavelength, dual-polarization radar allows information to be gleaned regarding the form of storm precipitation (ice crystal, small or large liquid droplet, hail). Its scan strategy was

normally tailored to focus on storms over the wind tower and field mill networks and to adequately sample the entire storm volume. Unfortunately, as will be seen in examples below, the WSR-88D three-dimensional storm coverage is often not totally adequate to accurately depict the upper portions of storms. (This is because the time-consuming need to monitor a full 360° of azimuth only allows a limited number of elevation angles to be scanned.)

1.2 PAST RESULTS AND CURRENT OBJECTIVES

This was the third summer of study involving research to utilize Lightning Detection and Ranging (LDAR) data, together with companion data sets, aimed at developing rules, algorithms, and training materials that can be used by the operational weather forecasters who issue weather advisories for daily ground operations and launches by NASA and the United States Air Force. Research during 1993 (ref 6) enabled the development of a computerized scheme for clustering the LDAR data into groups of data points associated with individual thunderstorms (as described above), tracking these LDAR-defined storms, and comparing the positions of the LDAR-detected lightning to those of other remote sensing systems. It was determined that LDAR-detected discharges aloft within the storm precede ground strikes by about 5 minutes in the region within 60 km of KSC, making LDAR a very useful tool for issuing very-short-term weather advisories and warnings. By recognizing and including storm movement in a forecast scheme, mappings of current LDAR data points can, to some degree of accuracy, be extrapolated with a storm motion vector to make forecasts of future cloud-ground strikes.

Research during 1993 showed, however, that beyond about 10 minutes areal storm growth and the development of new thunderstorm cells (as opposed to the translation of steady-state lightning patterns) became increasingly important factors in the prediction of future lightning ground strikes. Hence, one focus of the 1994 research (ref 7) was to include a storm growth factor in the forecast scheme. The 1994 study showed that only modest gains in forecast accuracy could be achieved through use of a symmetric growth factor, and that the sudden developments or decays of thunderstorm cells and their evolutions ultimately limited the accuracy of forecasts beyond about 10 minutes. Thus, research was begun to explore ways to use companion meteorological data sets and develop forecast schemes to help the forecasters anticipate new thunderstorm formation. In addition, forecasters must determine when the lightning threat at a site has ended--a task made difficult because electrified anvil clouds are often left behind above a site long after the core of the storm has exited the region. Thus, work was begun to examine this problem. Much of the work entailed the development of software to analyze and generate overlay displays of the various data sets.

The objectives of the 1995 research were to use the software that had been previously developed to perform a number of case studies, using 1994 and 1995 data. The goals of the case studies were to (1) examine relationships between lightning and storm structure as depicted by radar, (2) identify signatures in other data sets that can be useful in the forecasting of lightning, and seek guidelines and rules that forecasters might use in determining (3) where and when lightning ground strikes will first occur at a forecast site and (4) when the ground strike threat has ended at a forecast site. Table 1-1 lists the dates and character of the cases examined to date.

1.3 USE OF MULTIPLE DATA SETS IN LIGHTNING FORECASTING

Though each of the data sets mentioned contributes valuable information, none of the data sets alone are adequate to supply answers to all forecast decisions. Thus, the emphasis of this research will be to use multiple data sets in order to come up with the best overall forecast guidance.

TABLE 1-1
CASES EXAMINED USING RADAR, LDAR, LLP, LPLWS

10 June 1994, Day 161	--	Storm initiation on mesoscale boundary; quasi-horizontal discharges
1 July 1994, Day 182	--	Storm formation
18 July 1994, Day 199	--	Storm formation
19 July 1994, Day 200	--	Storm formation; impact of peripheral storms on LPLWS readings
29 July 1994, Day 210	--	Thunderstorm initiation; microburst storm
11 June 1995, Day 162	--	Storm formation through layered cloud at end of storm
12 June 1995, Day 163	--	Storm formation; end of storm cloud layer
20 June 1995, Day 171	--	Mostly lightning aloft
20 July 1995, Day 201	--	Storm formation
21 July 1995, Day 202	--	Storm formation through layered cloud at end of storm

When the forecaster is dealing with the problem of when to issue phase 2 lightning warnings (cloud-ground lightning imminent), the case studies suggest that there are limitations to the stand-alone capabilities of individual systems. (1) LDAR and LLP inherently only show the existence of lightning, but can help a forecaster anticipate when lightning from an approaching storm might become a threat at a particular site. (2) Furthermore, while the first LDAR discharges in a storm are typically aloft, and thus give a 4-5 minute lead time relative to ground strike threat, in about 25% of the storms the first ground strike occurs within a minute of the first appearance of LDAR. (3) In the cases studies, there are a number of instances where LDAR detects cloud-ground discharges that LLP does not detect. According to Launa Maier (personal communication), this tends to occur when the cloud-ground discharge is not very energetic. (4) However, LDAR also can fail to detect some ground strikes because of the dominance of the return stroke discharge at low levels (whereas LDAR detects stepped leader discharges). (5) Field mill readings can be large over a site in some instances long prior to any valid ground strike threat, due to electrified cloud blowoff from upwind storms or due to other low-level meteorological conditions. (6) On other occasions, with rapid storm development or small-diameter storms, the field mill readings may only become large briefly before lightning activity begins. Thus, the use of radar and surface mesonet data can yield invaluable clues regarding the location of thunderstorms and the state of their progress toward electrification.

When the forecaster is dealing with the problem of when to terminate the phase 2 lightning warnings (imminent ground strike threat has passed), case studies again indicate that no individual data set is adequate. (1) LDAR often shows the existence of extensive quasi-horizontal discharge patterns aloft long after ground strikes have ceased. (2) LLP may misrepresent some discharges aloft as ground strikes. (3) LDAR may fail to detect some ground strikes, as noted above. (4) Field mill readings can remain large long after the ground strike threat has ceased, due to lingering electrified cloud layers overhead or nearby.

II. GROUND STRIKE PROBABILITY IN RELATION TO LDAR PATTERN AND RADAR ECHO

Results from the 1993 studies (ref 6) indicate that within the concurrent minute, 85% of the LLP-detected ground strikes occurred within the bounds of the LDAR discharge pattern, and 98% of the ground strikes occurred within or no more than 2 km beyond the edge of the LDAR pattern. These data were combined with storm diameter to come up with a composite risk analysis for ground strike threat during the next minute relative to the current LDAR pattern. Ground strike probability has been computed as a function of radius from the LDAR pattern center per unit area within a series of concentric rings, and is plotted as Figure 1-1. Also shown is the edge of the composite LDAR data pattern. The absolute probability of a ground strike decreases from about $0.01 \text{ km}^{-2}\text{min}^{-1}$ near the center of the LDAR pattern, to about 0.001 near the edge of the LDAR pattern, to about 10^{-4} at about 3 km beyond the edge of the LDAR pattern and to about $10^{-5} \text{ km}^{-2}\text{min}^{-1}$ at about 6 km beyond the edge of the LDAR pattern. Statistics were compiled from 319 LDAR-detected thunderstorms that occurred during 33 hours on 13 days in June and July 1993 and within +/- 52 km west/east and +/- 40 km north/south of KSC.

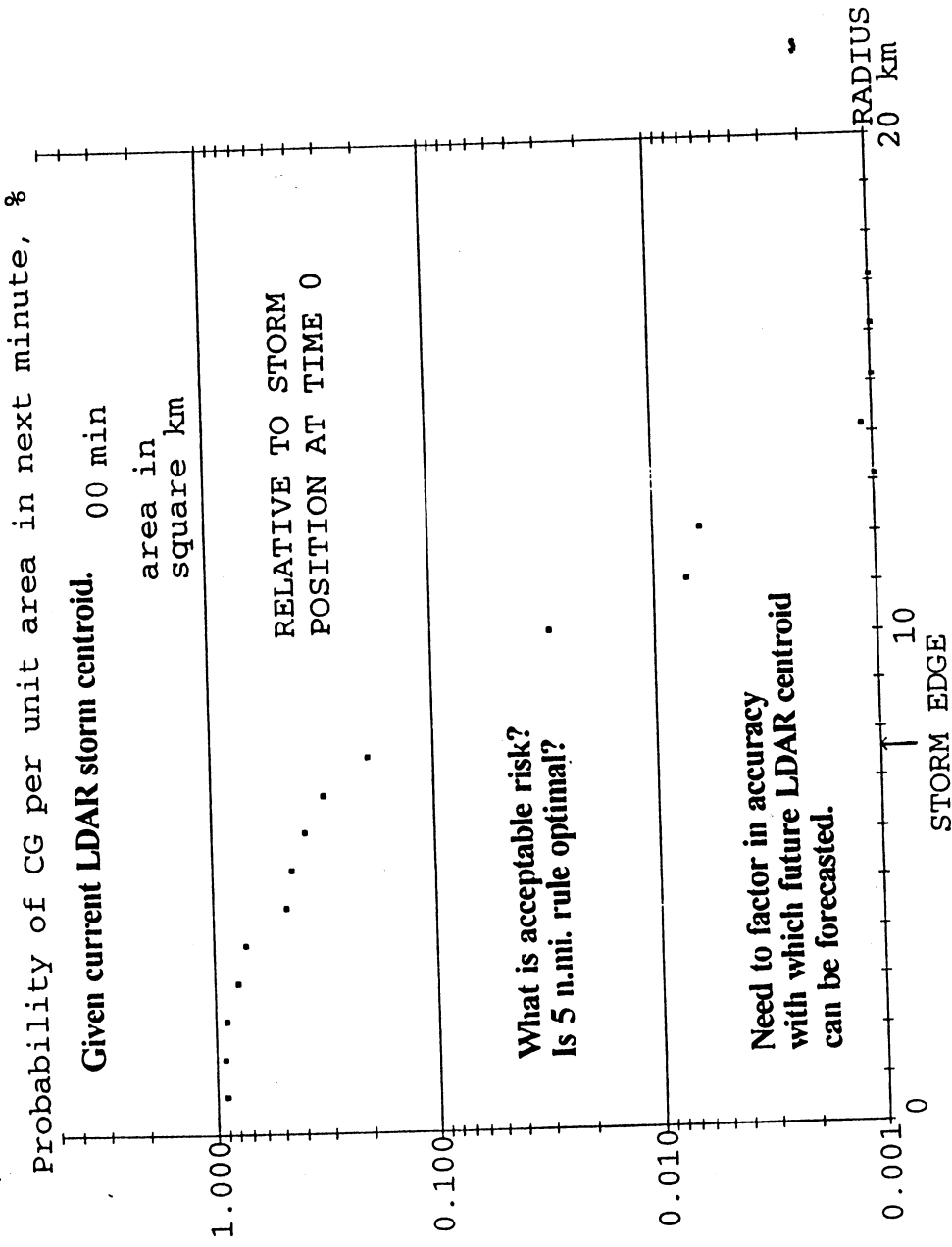


Figure 2-1. Probability of a lightning ground strike within one minute, given the current position of the center of the LDAR discharge pattern, as a function of distance. Probability (y-axis) is in percent per square kilometer. Position of the edge of the composite LDAR pattern edge is indicated by arrow.

During the inspection of the cases to date (Table 1-1) it became obvious that the great majority of ground strikes occur near or within regions experiencing low-level precipitation. As a working rule, lightning rarely strikes ground more than 2 km beyond the edge of the 20 dBZ reflectivity contour in the lowest 4 km. However, exceptions do occur. Figure 2-1 shows the two most extreme cloud-ground strikes, identified within the cases examined to date. In these cases the discharge appears to have travelled toward ground in locations outside cloud edge for at least a portion of the path. The ground strike position in these cases is about 6 and 5 km, respectively, from the 20 dBZ position.

It also became obvious that LDAR and LLP do not always give exactly the same numbers and locations of ground strikes. There are daily examples where LDAR shows strings of data points progressing to within a kilometer of the surface, and which are inevitably ground strikes, that are not shown by LLP. Presumably these flashes had weak return strokes that were missed by LLP. Similarly, LLP daily records ground strikes not accompanied by LDAR points near the surface. This is not totally surprising, since LDAR detects stepped leaders and, in contrast, return strokes dominate the low-level portion of ground strikes. However, on some occasions the LLP points may be erroneous representations of discharges aloft as ground strikes.

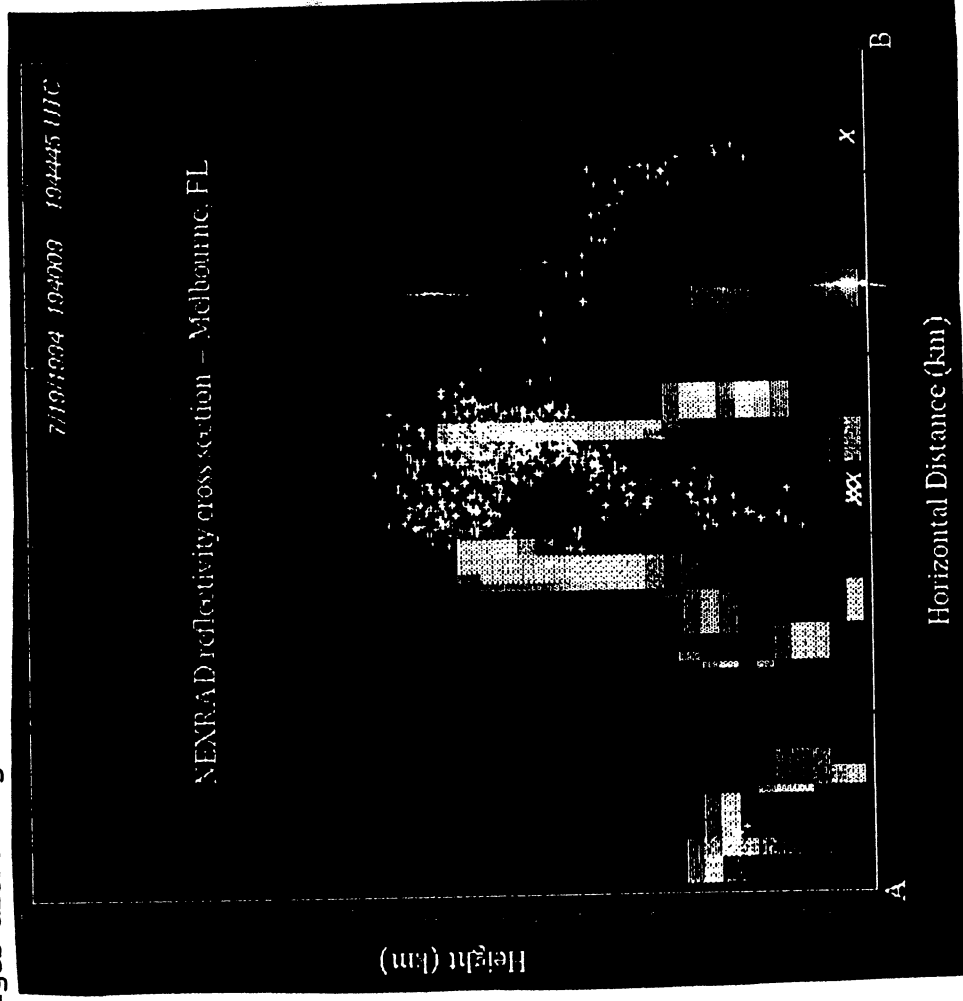


Figure 2-2. Examples of ground strikes in low-reflectivity regions, depicted by LDAR (+ symbols) and LLP (X) overlaid onto cross-section of radar reflectivity. Because the original is in color, reflectivities are hard to distinguish in black and white. Because the radar scanned only at a few elevation angles, storm top in (a) is not depicted.
a. from 19 July 1994

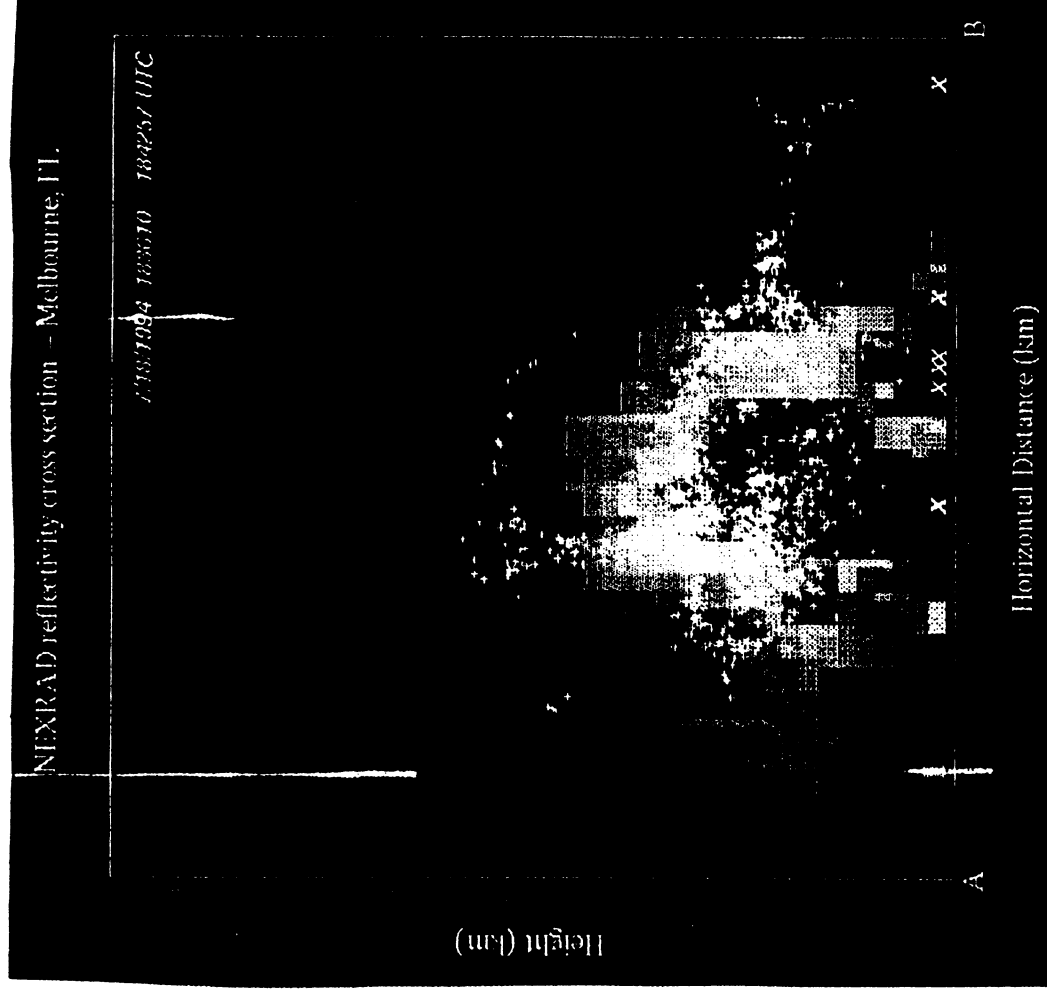


Figure 2-2. Examples of ground strikes in low-reflectivity regions, depicted by LDAR (+ symbols) and LLP (X) overlaid onto cross-section of radar reflectivity. Because the original is in color, reflectivities are hard to distinguish in black and white. Because the radar scanned only at a few elevation angles, storm top in (a) is not depicted.

b. 18 July 1994 .

In order to identify the first and last times of ground strikes affecting (i.e., within 5 n.mi. of) any warning site in the cases studied to date (Table 1-1), the initial and final LLPs of each case were compared to the LDAR data at the time. Many additional discharges were examined by watching the real-time LDAR and LLP displays. Based upon the combined information, an approximate scheme was formulated to identify when an LDAR flash was likely to have yielded a ground strike:

- a. There must be at least two LDAR points below altitude of 3 km;
- b. At least one of the LDAR points must be below 2.1 km;
- c. The lowest LDAR point must be within a slant distance of not more than 2 km from another LDAR point;
- d. LDAR points near $x = -1.3$, $y = -1.6$ km and below 600 m within the first 0.006 second of each minute must be viewed suspiciously, as these are likely to be due to a calibration pulse emitted from an antenna on the top of the NASA Central Instrumentation Facility building.

III. JOINT USE OF METEOROLOGICAL DATA SETS IN FORECASTING INITIAL LIGHTNING THREAT

Many studies (e.g., ref 8) have shown that the location of thunderstorm initiation can often be inferred through careful use of satellite, radar, and surface data. Radar and satellite can reveal the initial development of small clouds in areas of enhanced ascent due to low-level convergence where the winds from small-scale features such as the sea-breeze, river breeze, or thunderstorm outflow collide with the prevailing large-scale wind. Wind and temperature patterns shown by the KSC wind tower mesonetwork can also reveal these convergence zones and local hot spots of enhanced buoyancy.

The surface mesonetwork can reveal preferred areas of thunderstorm development:

- a. Strong convergence precedes new thunderstorm development;
- b. New thunderstorm development is enhanced where convergence intersects a thermal (buoyant) plume or thermal boundary (mesoscale front);
- c. Development is enhanced where convergence intersects the gradient between a region of temperature change over the last 15 to 30 minutes, with warming on at least one side of the gradient;
- d. Sites of future maximum convergence are sometimes revealed by charts showing wind vector change over the last 15 to 30 minutes.
Convergence of these streamlines highlight regions becoming more convergent with time.

Figures 3-1 and 3-2 illustrate the above rules, using real data from 18 July 1994. Figure 3-1a shows the surface mesonet data from 1650 UTC, and Fig. 3-1b shows the change in temperature in the straddling period ending at 1700 UTC. Figure 3-2 shows the streamlines and convergence at 1650. The data show a well-defined convergence zone over Merritt Island near KSC between the Banana and Indian Rivers that is also warming with time, whereas the adjacent regions have remained constant or cooled. Temperatures just south of the convergence center were already warm and are becoming even more buoyant. This combination of convergence (which will force upward motion and help trigger cloud formation) and buoyancy suggests a preferred location for thunderstorm initiation over or just west of KSC on this occasion. Vector changes of the wind (not) shown, also indicate a need to focus on this location.

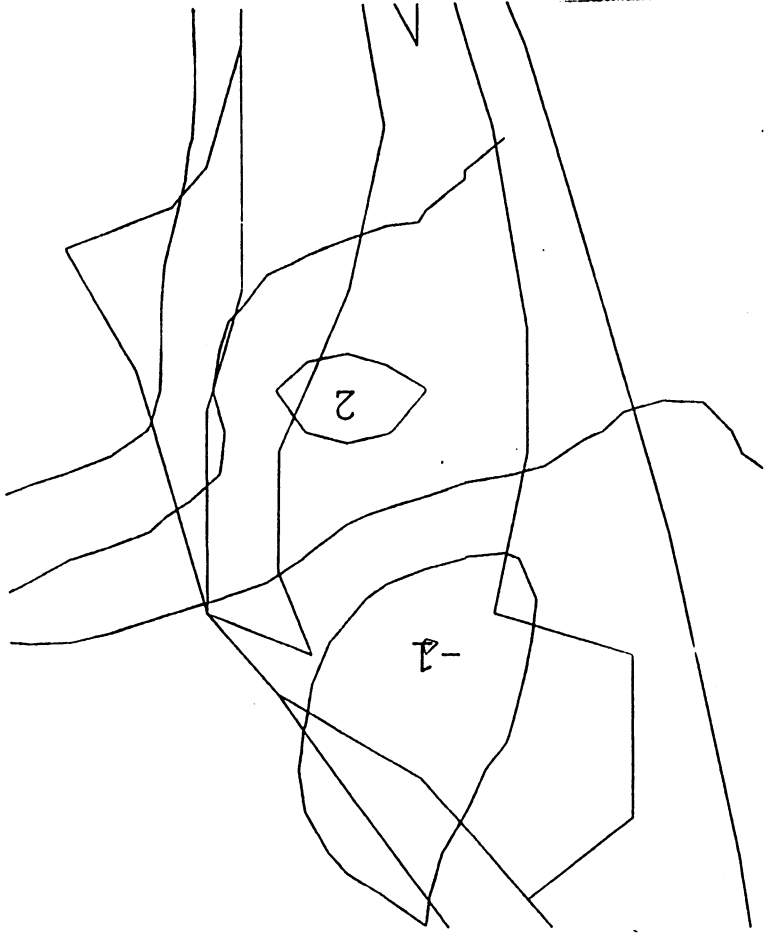
Figure 3-3 shows the first radar composite (from 1704-1708 UTC) with precipitation in the developing thunderstorm. In the preceding 5 minutes the reflectivity has increased from 10 dBZ and is now in excess of 30 dBZ. Though the radar scan strategy is chopping off the top of the echo in the cross-section, reflectivities exceed 30 dBZ at 8 km, suggesting that lightning is imminent in this storm.

Figure 3-4 shows that the storm also has marked storm-top divergence. There is also convergence at low levels near range of 8 km along the cross section. Hence, the storm should have a vigorous updraft, and precipitation-powered electrification should be well underway.

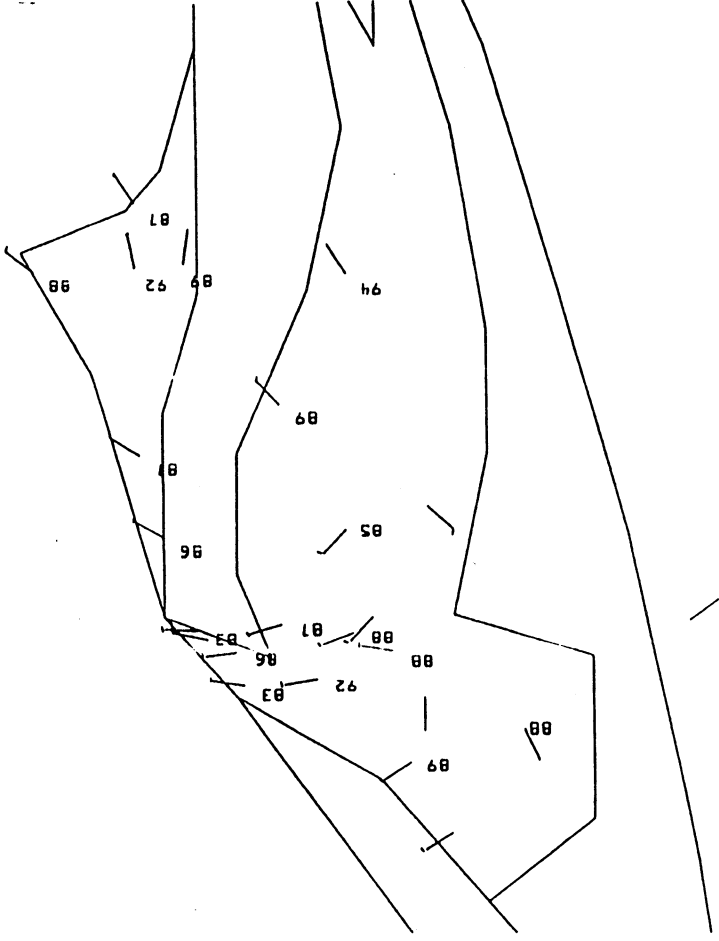
Figure 3-5 shows the radar composite from 1709-1714 UTC. Maximum reflectivity in the storm is now about 50 dBZ and exceeds 40 dBZ at 8 km altitude. Such a storm should be producing lightning. Indeed, LDAR events commenced at 1709 UTC in the layer between 8.2 and 10.4 km just above the reflectivity core, and have begun to discharge outward as superimposed on the imagery. A newer cell to the north does not yet have high enough reflectivity (30 dBZ) or altitude (8 km) to be producing lightning. Though not shown here, one surface field mill exceeded 1 kV/m at 1711 when data first became available, but this storm is in general too young and too small to have impacted many of the field mills at this stage.

Figure 3-1. Surface mesonet data from 1650 UTC on 18 July 1994 (left) and isotherms of the 15-minute temperature change (right) ending at 1700 (°F).

15-minute T change ending 1700 UTC



7/18/94 Day 199 1650 Surface Plot



7/18/94 Day 199 1650 UTC Streamlines and Divergence



Figure 3-2. Streamlines (left) and divergence (right) of the surface wind at 1650 UTC on 18 July 1994. Divergences are in units of $10^{-5} s^{-1}$.

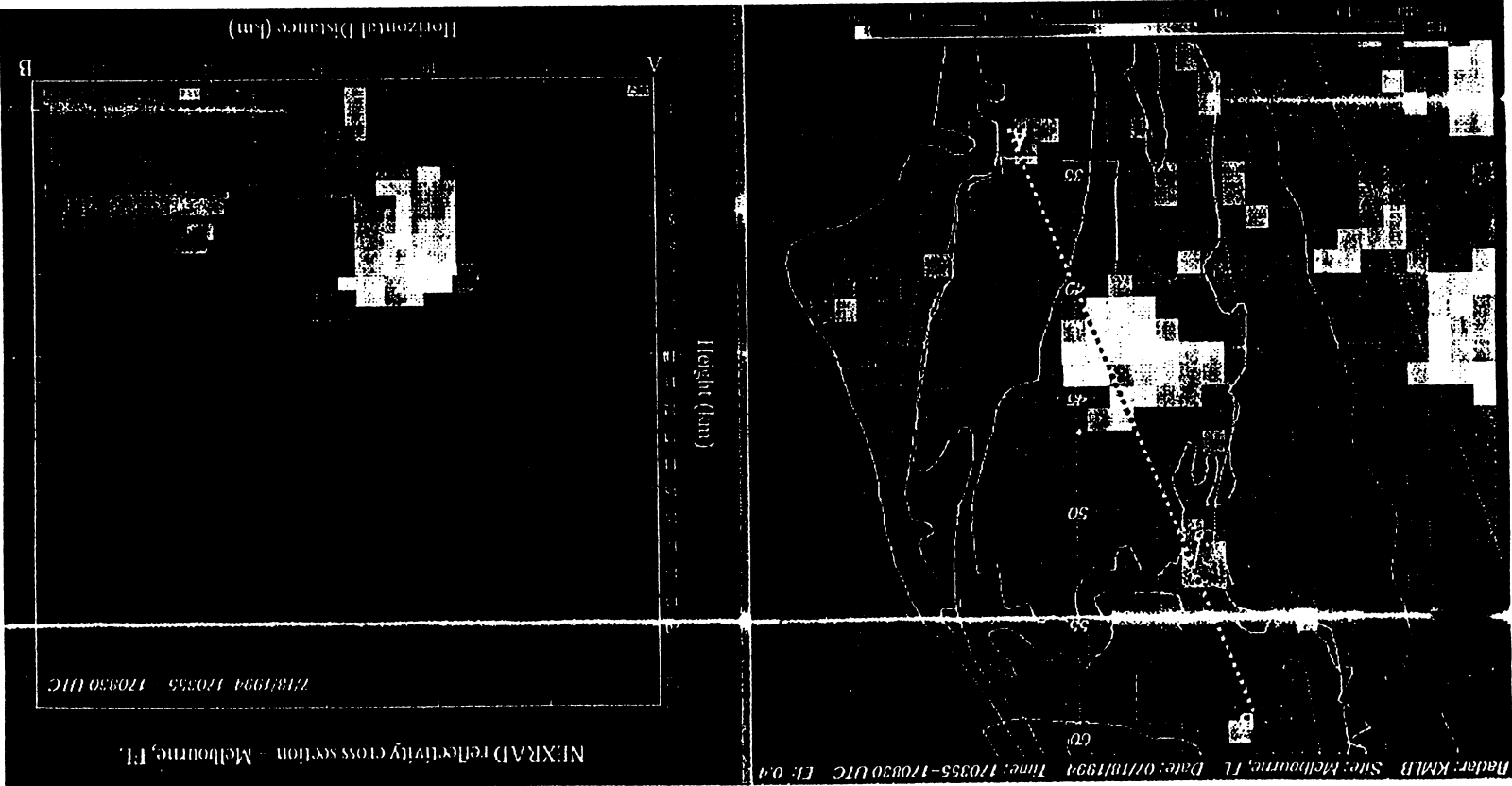


Figure 3-3. Radar depiction of the initial storm development, using National Weather Service WSR-88D data from Melbourne, FL. Left, composite reflectivity (highest in the column); right, vertical cross section. Original was in color, so reflectivity shadings do not reproduce well in black and white. Sampled from about 1704-1708 UTC, 18 July 1994.



Figure 3-4. Doppler velocities in the storm of Fig. 3-3. Left, velocities in the north and negative (southbound) in the southern portion of the storm, indicating divergence. Right, cross-section view.

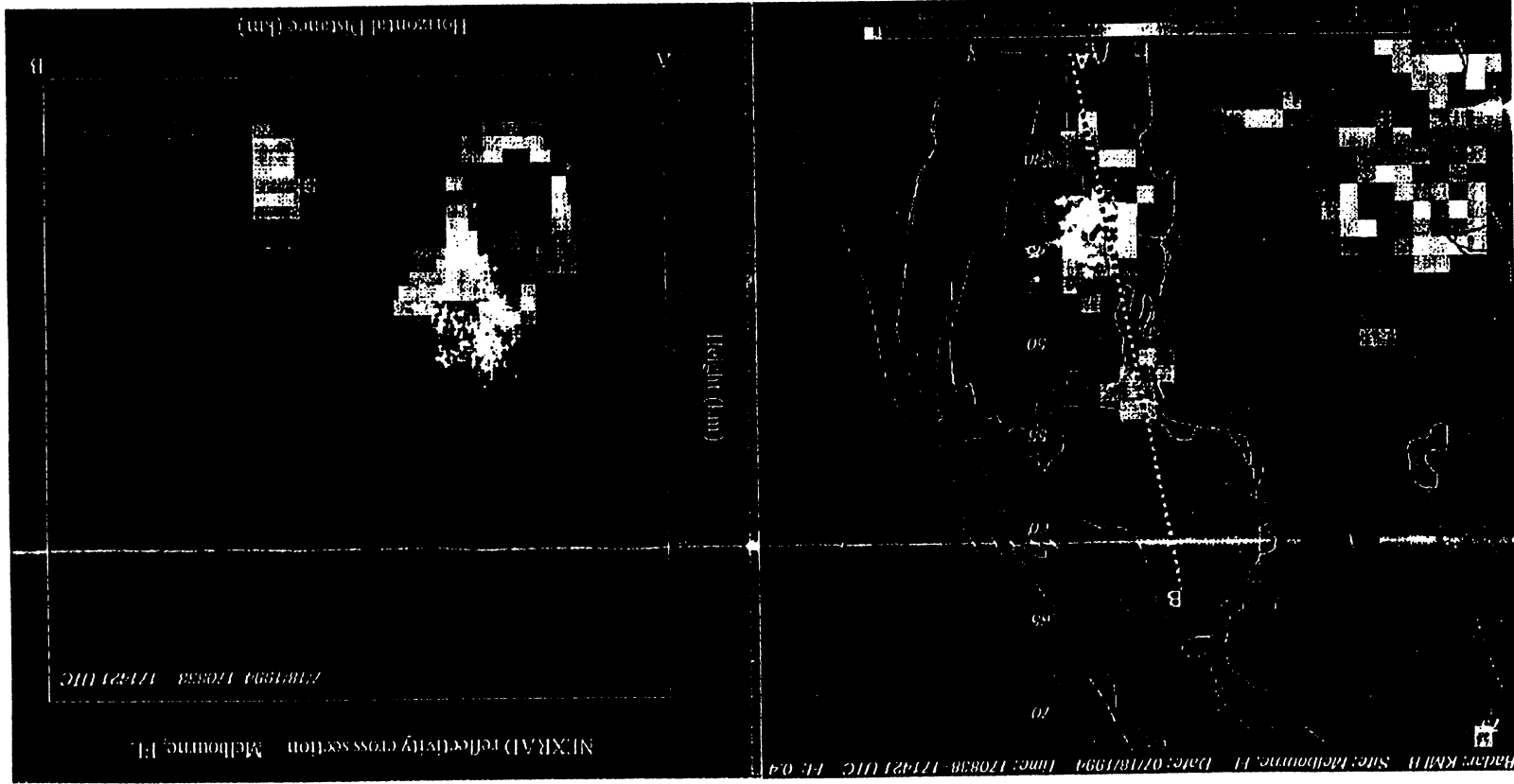


Figure 3-5. Radar and LDAR depiction of the storm from 1709-1714 UTC. Left, composite reflectivity with LDAR data for this time interval superimposed (white + symbols). Right, cross-section, including LDAR data within 1 km of the cross-section.

Figure 3-6 shows the pair of radar echoes composited for the period 1715 to 1721 UTC, with LDAR data superimposed. The thunderstorm developed ground strikes beginning at 1716, and has also begun to produce quasi-horizontal flashes radiating outward. Figure 3-7 shows that the region of initiation of these quasi-horizontal discharges is within the area of divergence in the upper half of the storm, consistent with being in updraft.

The storm soon began to show a collapsing top, and all LDAR activity ceased at 1743. Case studies suggest that in individual thunderstorms lightning activity begins and ends when the 30 dBZ echo (or greater) appears and then disappears from altitudes of at least 8 km.

IV. JOINT USE OF METEOROLOGICAL DATA SETS IN FORECASTING TERMINATION OF LIGHTNING THREAT

In some ways forecasting when the threat of ground strikes to a region has ended is a more challenging meteorological problem than in predicting where and when the first ground strike will occur. The case studies to date suggest that on many of the former occasions there will be ongoing quasi-horizontal LDAR discharges aloft long after the last ground strike has actually occurred, but the safe assumption is that ground strikes remain a possibility as long as there are LDAR events aloft. Furthermore, the case studies show that surface field mill readings can remain quite high long after the last ground strike has actually occurred, due to the presence of charged anvil or debris cloud overhead or nearby. Unfortunately, there are documented cases in the literature of ground strikes emanating from anvils, so that cautious forecasting is merited. Thus, most rules that would allow the termination of phase 2 advisories in the presence of LDAR discharges or large electric fields implicitly involve accepting some level of risk. Unfortunately, the data base may be inadequate to properly quantify what is the level of risk involved. Certainly we have not yet performed enough case studies to quantify the risk as a function of radar reflectivity, LDAR discharge rate or intensity, or other factors.

Figure 3-8 shows an example of the problem faced by the forecaster. The last ground strike within 5 n.mi. of any warning site in this case was at 2100 UTC. However, there are still LDAR discharges within the clouds aloft, and surface field mill readings remain high. Even by 2130, 16 sites still exceed $+/- 1$ kV/m. Clearly the site with the 1.7 kV/m field mill reading is not under a very great risk of a ground strike, as there is only a rather thin anvil cloud above it. A working hypothesis has been formulated based upon our case studies, but one that is statistically untested in terms of absolute risk of ground strike: ground strikes are uncommon at points more than 2 km beyond where the edge of the 20 dBZ contour is found within the lowest 4 km of the storm.

Figures 3-9 and 3-10 show another example, where sloping layers of LDAR discharges are found in the reflectivity gradients at the top and bottom of the anvil. The upper LDAR layer of Fig. 3-9 extends farther to the rear of the eastward-moving storm than does the lower layer. Field mill readings at the surface (Fig. 3-10) fall below 1 kV/m beneath the extended LDAR layer. Adoption of the "2 km beyond 20 dBZ" rule above in this case would call for an end to the ground strike threat at about the 24 km range along the cross-section of Fig. 3-9, whereas the upper LDAR layer ends at about the 22 km range.

The cross section of Fig. 3-10 intersects a surface-based slice of reflectivity greater than 20 dBZ, centered near 30 km along the section. A simple adoption of the hypothetical rule above would terminate the ground strike threat at about the 26 km range on the section. However, intercomparison with Fig. 3-9 shows that this cloud layer is not the one being straddled by the layered LDAR points. Indeed, there are no LDAR points along the cross section in this region of enhanced reflectivity. It would be tempting, then, to terminate the ground strike threat at about the 39 km range on the cross section.



Figure 3-6. Radar and LIDAR depiction of the storm from 1715-1721 UTC. Left, composite reflectivity with LIDAR and LTP (black X) superimposed. Right, cross-section.

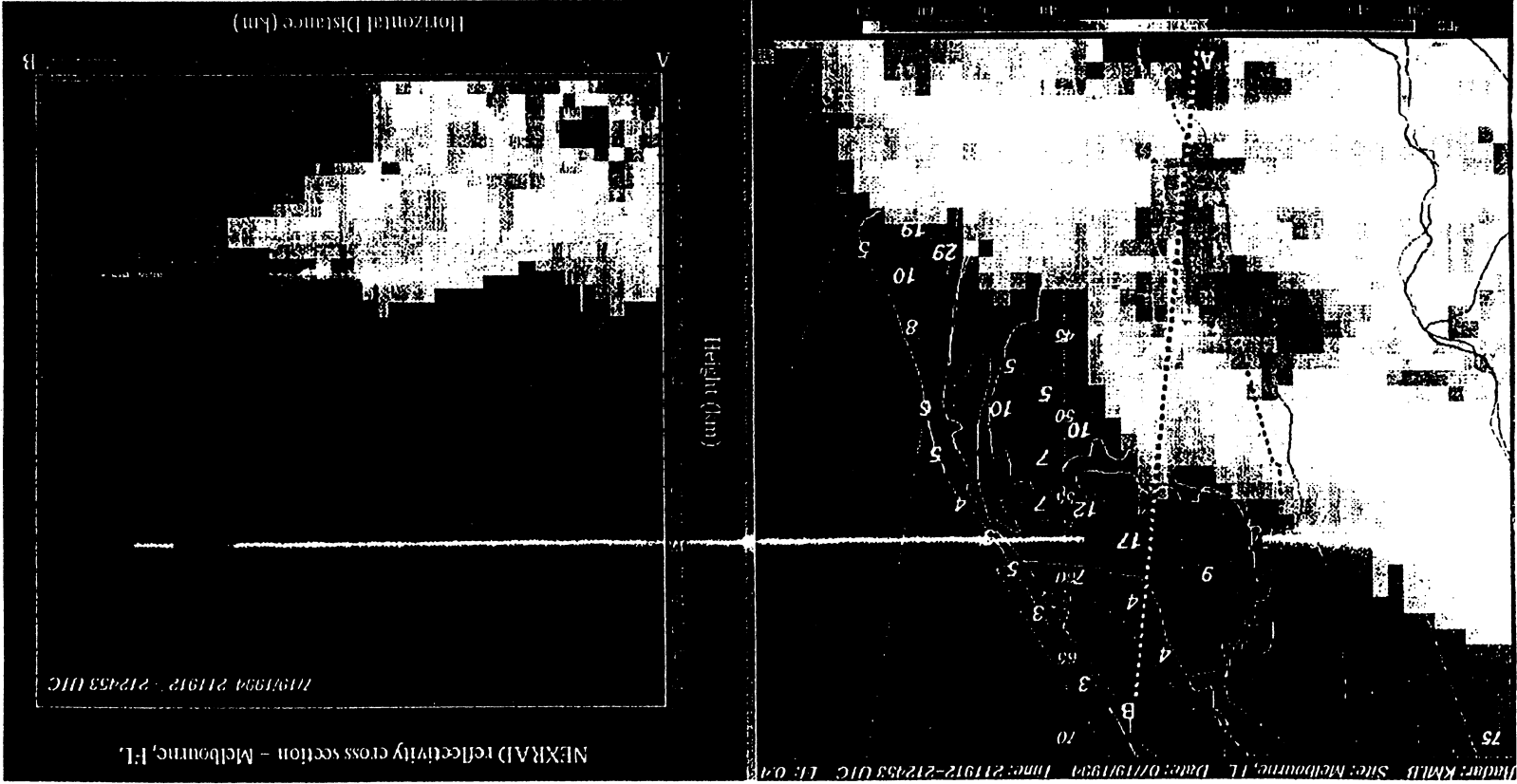


Figure 3-8. Radar depiction of the post-threat storm on 19 July 1994, from 2119-2125 UTC. Left, composite reflectivity and one-minute-average field mill (LPLMS) values from 2120, in tenths of kV/m. Right, cross-section.

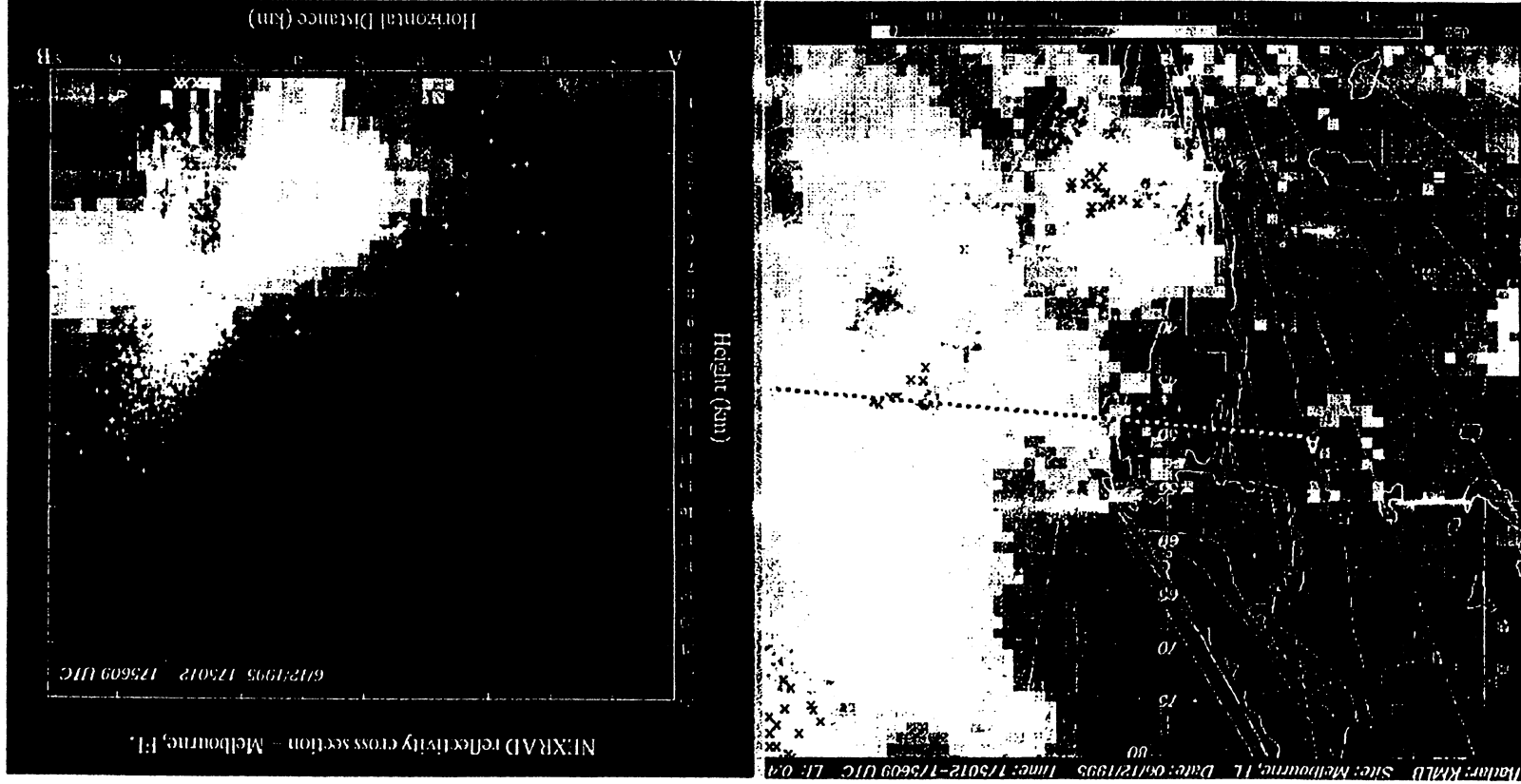


Figure 3-9. Radar and LDAR depiction of the post-threat storm on 12 June 1995, from 1750-1756 UTC. Left, composite reflectivity, LDAR (white + symbols), and ILP (black x). Right, cross-section.

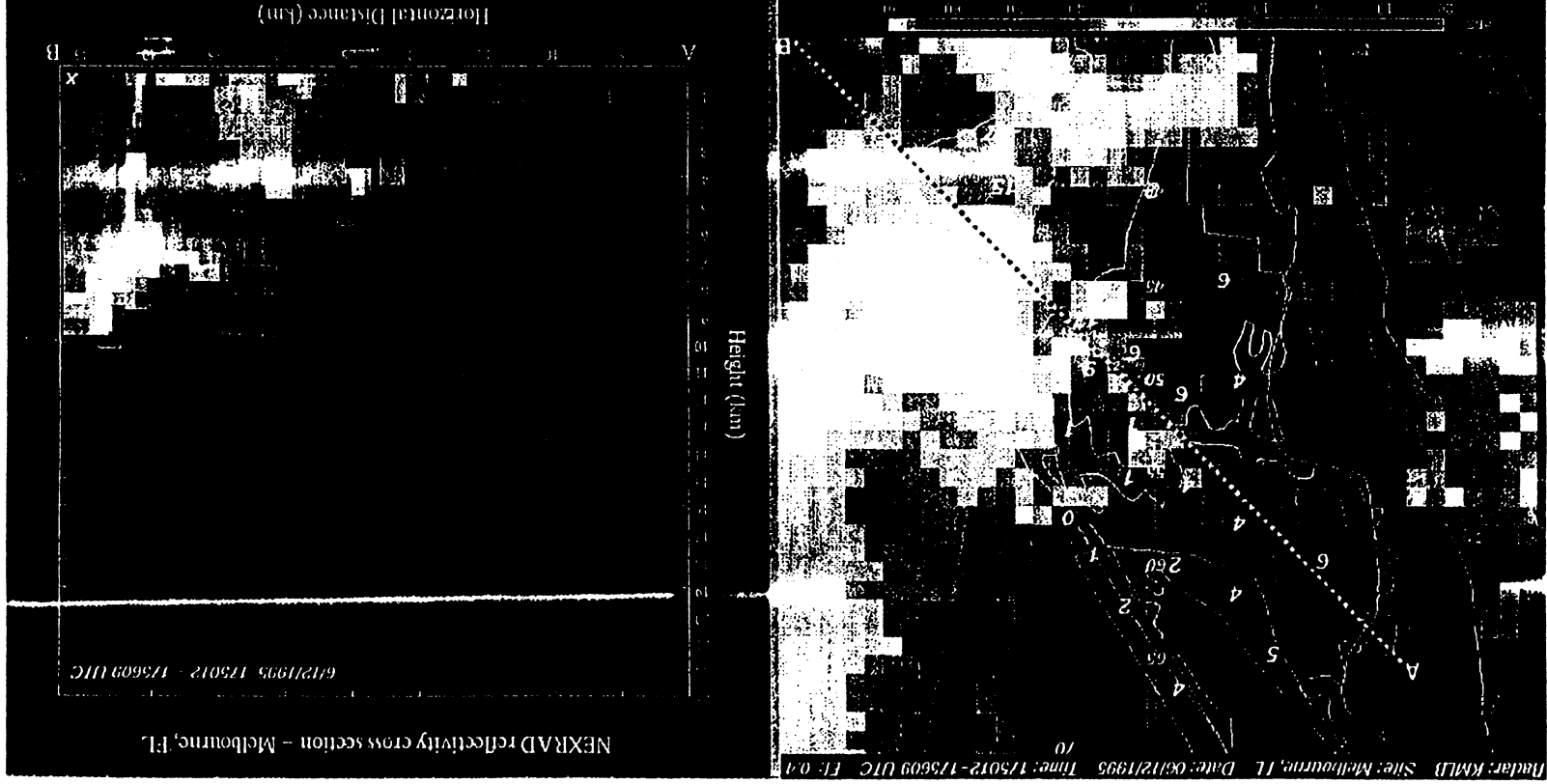


Figure 3-10. Radar and field mill data corresponding to Fig. 3-9. Left, composite reflectivity and one-minute-average field mill (LPLMS) values from 1755, in tenths of kV/m. Right, cross-section.

Figure 3-11 is from a day where lightning was from convective accentuations of more widespread layered or banded clouds. Use of maximum reflectivity as a crude lightning location predictor on this occasion would have given a very poor portrayal of the locations of peak lightning threat, as shown. Lightning on this occasion emanated from regions where sufficiently large reflectivity occurred at higher altitudes. On this day of more mesoscale rather than purely buoyant convective forcing, it appears that lightning was initiated where and when 30 dBZ echo occurred above the 7 km level. As shown in Fig. 3-11, the LDAR discharges then propagated along the top of the cloud and along the gradient atop the region of highest reflectivities. This resulted in primarily a downward slope, except near about 25 km on the section where a localized turret elevated cloud top for a short distance. Ground strikes were quite uncommon on this day, as only 5 ground strikes were indicated within 5 n.mi. of any warning site using both LDAR and LLP to detect ground strikes.

Figure 3-12 shows another LDAR discharge pattern on this occasion, and the only ground strike indicated by both LDAR and LLP. Once again the LDAR discharge pattern appears to have initiated not from the region of highest reflectivity but from the region of highest reflectivity above a critical altitude, at position near 10 km along the cross section. Use of the hypothesized 20 dBZ edge rule would have been difficult in this case, as there is so much low-level echo above 20 dBZ. Further, this case points out a potential danger in the inference drawn regarding Fig. 3-10. In that case a lower layer of echo > 20 dBZ was ignored because it was not the one in which LDAR discharges were occurring. In the case of Fig. 3-12, an echo from low-levels protruded upward into the base of the LDAR layer, perhaps not coincidentally becoming the site for a ground strike. Clearly additional study is needed to clarify the circumstances under which ground strikes occur beneath primarily layered LDAR discharges.

Figure 3-13 shows echo from the same case at a later stage. All ground strikes affecting any warning site have ended as of 2323, though field mill readings remain very large. A working hypothesis in this case might have been that the ground strike threat would cease once 30 dBZ echo no longer reached the 7 km level. Additional study of the meteorological bases for phase 2 termination is needed.

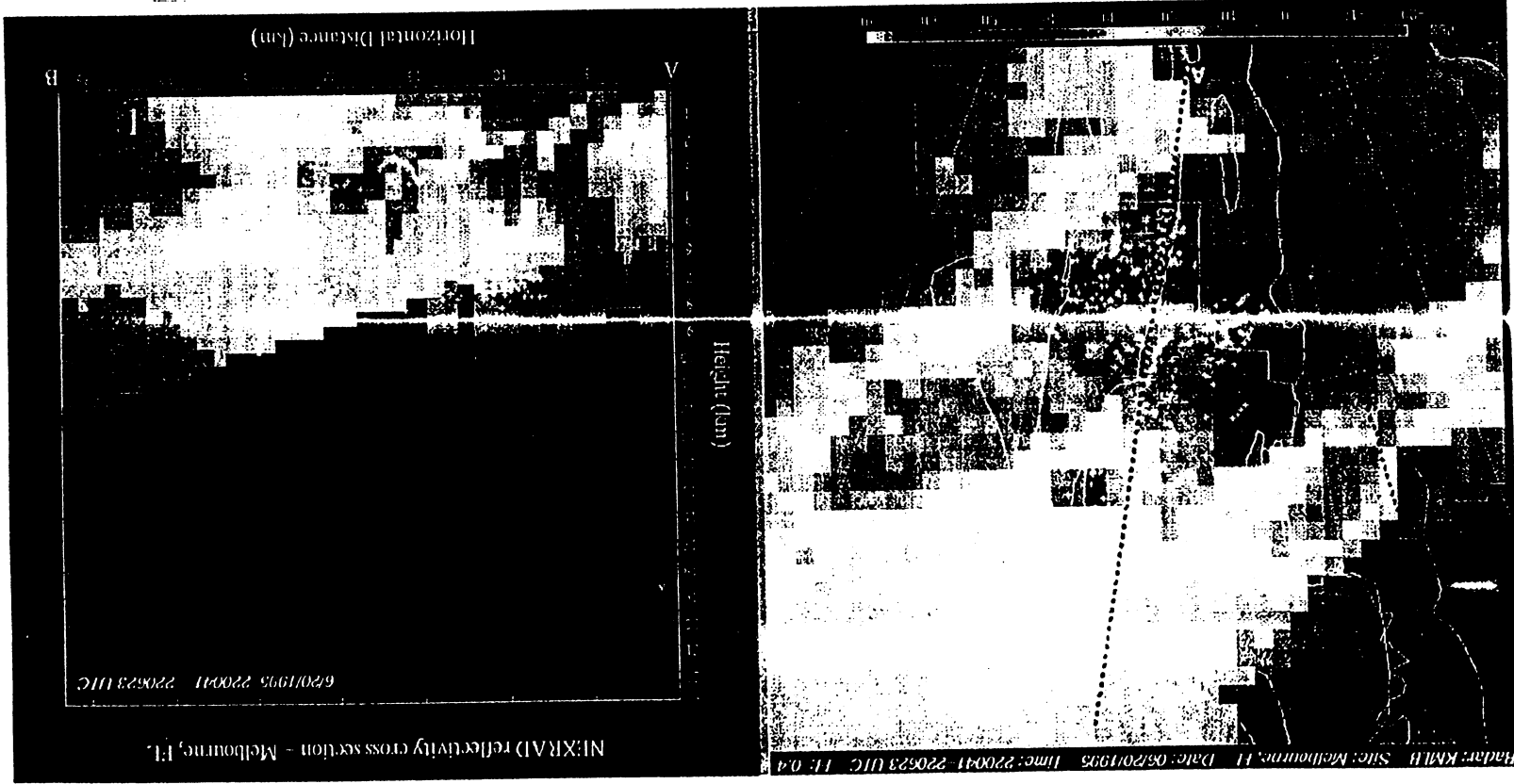


Figure 3-11. Radar and LDAR depiction of quasi-horizontal lightning layers on 20 June 1995 from 2201-2206. Left, composite reflectivity and LDAR. Right, cross-section.

NI:XRAD reflectivity cross section - Melbourne, FL

6/20/1995 220041 220623 UTC

Radar: KMLH Site: Melbourne, FL Date: 06/20/1995 Time: 220041-220623 UTC HF: 0.4

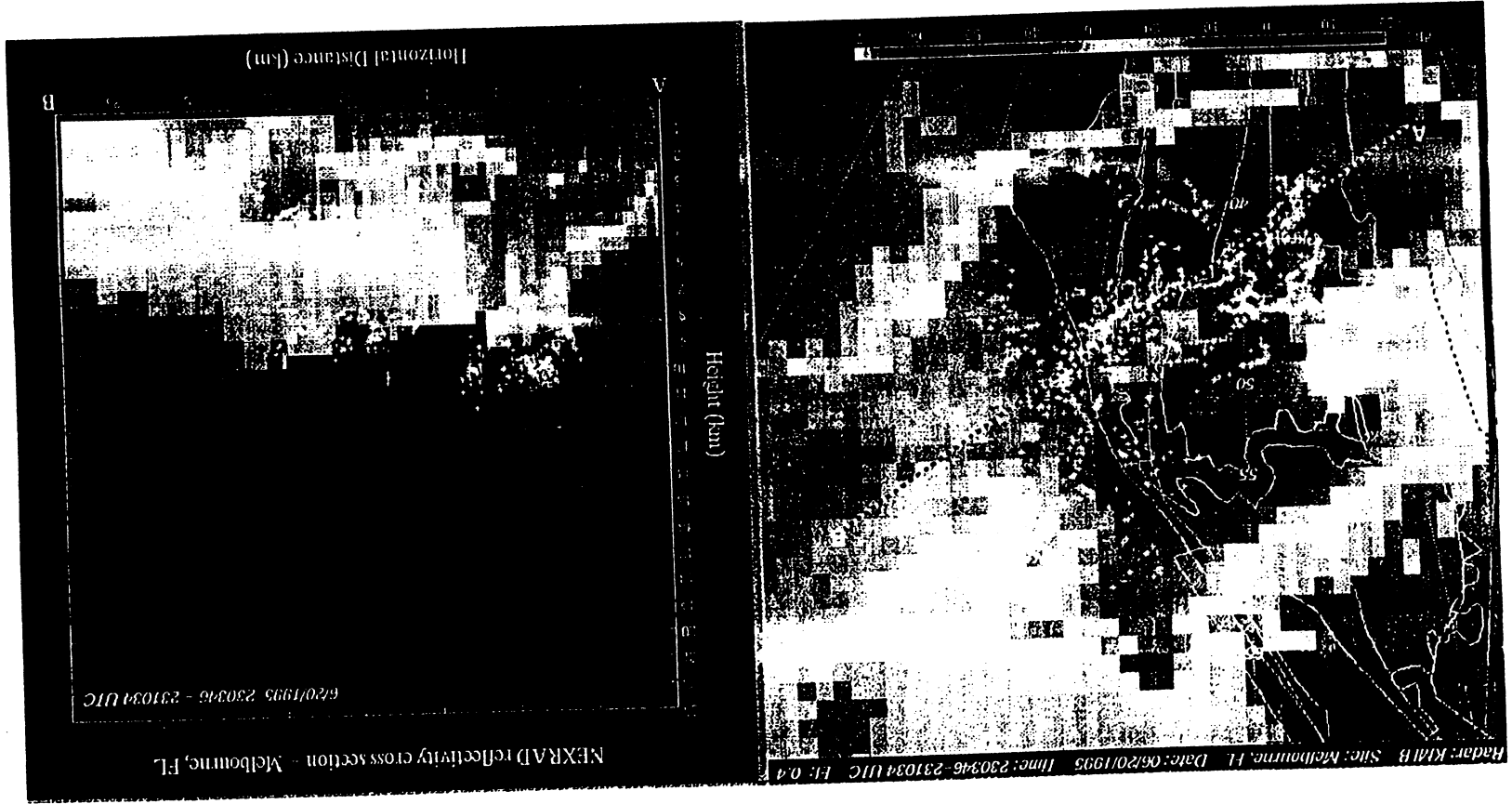


Figure 3-12. Radar and LDAR depiction of this case, including a ground strike, from 20 June 1995, 2304-2310 UTC.

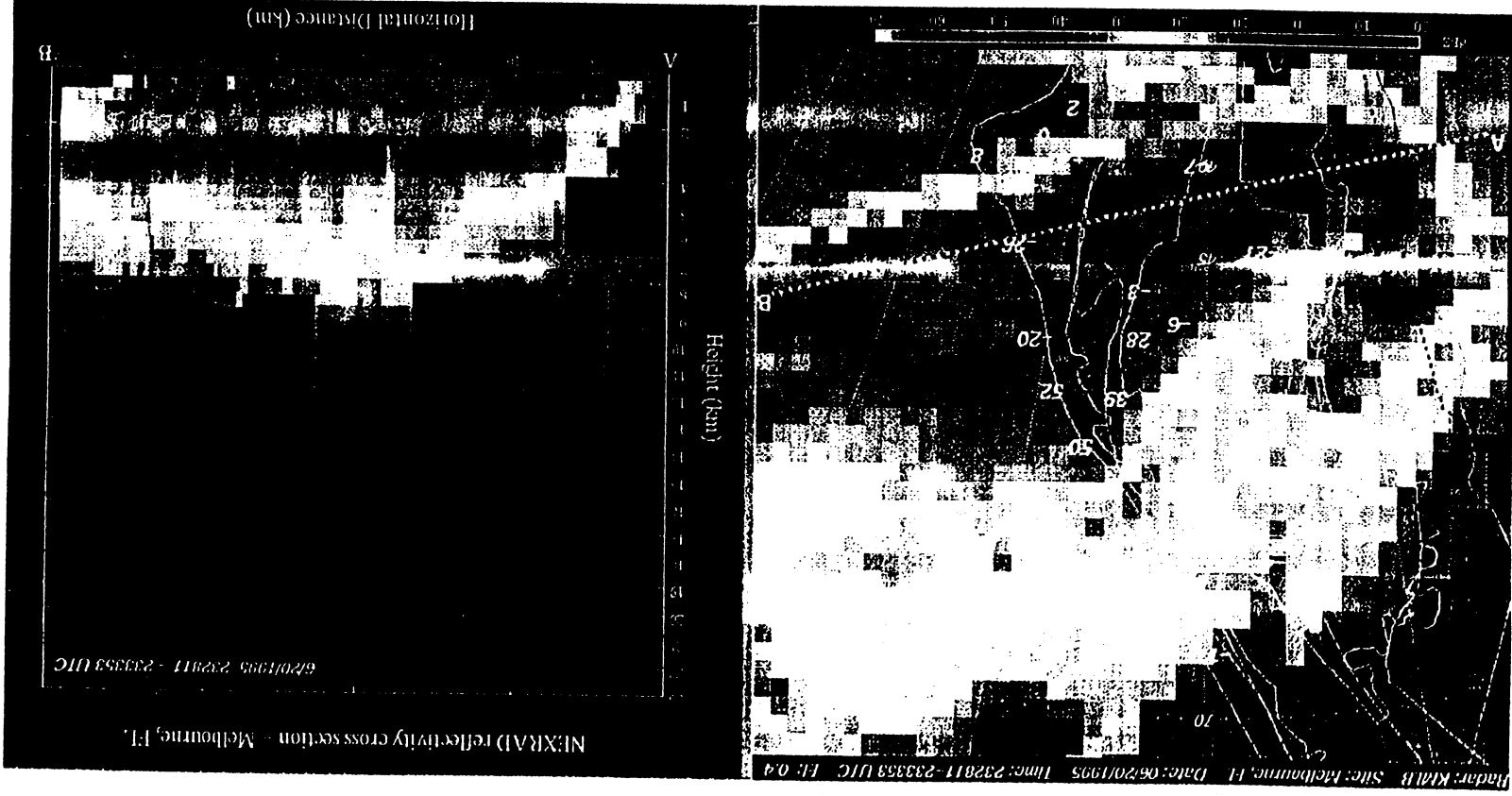


Figure 3-13 Radar and field mill depiction of the storm at a later stage, at the time of the last ground strike that affected any warning area. From 20 June 1995, 2328-2334 UTC. Left, composite reflectivity and one-minute-average field mill (LPLMS) readings from 2331, in tenths of KV/m. Right, cross-section.

V. CONCLUDING REMARKS

A strong case can be made for utilization of all available meteorological data sets in the forecasting of lightning. In particular, the forecasting of the in situ development of thunderstorms over the warning sites requires information beyond LDAR and LLP data, which only indicate when lightning has developed. Field mills sometimes provide advance information in these cases, but the use of radar, satellite, and surface wind tower mesonet data is also crucial. Likewise, it is difficult to be sure that lightning ground strikes have ended without the use of field mill and especially radar data to augment the LDAR and LLP data.

To most effectively use the various data sets, they should be overlaid on radar or satellite imagery. We have developed a software package that allows LDAR, LLP, field mill, and surface data to be overlaid onto radar imagery, as illustrated in this report. The software package produces plan and cross-section views of the radar and overlaid data sets. It can also produce maps of composite reflectivity (largest value in the column above each point), storm tops, and vertically integrated liquid water content (VIL). Additionally, we have developed software to implement the Velocity-Azimuth-Display (VAD) method for generating time-height series of mean wind, deformation, divergence and vertical velocity above the radar. The software package currently runs with archived data sets, but is expected to be adaptable for real-time use.

We have used the display software to examine 10 cases from June and July of 1994 and 1995. Some preliminary conclusions have been drawn, but they should be examined in more detail with further case studies, or examined on a real-time basis.

1. Radar, satellite, and surface mesonet data can help to pinpoint the location of thunderstorm formation. Mesoscale boundary detection, through use of satellite and radar imagery, streamline and convergence plots, temperature and temperature change plots, and vector wind change plots can yield valuable clues.
2. Lightning did not first appear in most developing thunderstorms until a sufficient mass of precipitation had developed at levels where temperatures at least as cold as -15 to -20°C would allow mixed-phase electrification processes to operate. Thresholds suggested to date are 30 dBZ or greater at altitudes of at least 8 km. Storm-top divergence should be monitored to help anticipate whether storms approaching this threshold are still in a growth stage (still divergent aloft).
3. In one case of small-scale convection embedded within larger-scale forcing, attaining 30 dBZ at 7 km appeared to be sufficient to initiate lightning.
4. The end-of-threat lightning forecast appears to require just as much, if not more, meteorological judgement. In most cases lightning did not strike ground more than about 2 km outside regions of the storm where low-level (0-4 km) reflectivities fell below 20 dBZ. However, there were notable exceptions.
5. Field mill readings typically remained above 1 kV/m tens of minutes or more after ground strikes had ended at a site, due to layered cloud left behind after the thunderstorm core had passed. Additional study is needed to determine joint meteorological conditions that enable forecasts of lightning threat cessation that are maximally safe and yet not overly cautious.

REFERENCES

1. Maier, M.W., A.G. Boulanger, and R.I. Sax: An initial assessment of flash density and peak current characteristics of lightning flashes to ground in South Florida. NUREG/CR-1024, U.S. Nuclear Regulatory Commission, 1979.
2. MacGorman, D.R., M.W. Maier, W.D. Rust: Lightning strike density for the contiguous United States from thunderstorm duration records. NUREG/CR-3759, U.S. Nuclear Regulatory Commission, 1984.
3. Maier, L.M., E.P. Krider, and M.W. Maier: Average diurnal variation of summer lightning over the Florida Peninsula. *Mon. Weather Rev.*, 112(6), June, 1984, pp. 1134-40.
4. Krider, E.P., A.E. Pifer and D.L. Vance: Lightning direction-finding system for forest fire detection. *Bull. Amer. Meteorological Soc.*, 61, 1980, pp. 980-86.
5. Lemmon, C. and L. Maier: Lightning mapping system. NASA CP-3106, Vol. II, 1991 International Aerospace and Ground Conference on Lightning and Static Electricity, 1991, pp. 89-1 to 89-10.
6. Forbes, G.S.: Lightning studies using LDAR and LLP data and applications to weather forecasting at KSC. 1993 Research Reports, NASA/ASEE Summer Faculty Fellowship Program (C.R. Hosler, C. Valdes, T. Brown, eds.), NASA CR-194678, Grant NGT-60002 Supplement 11, 1993, pp. 165-194.
7. Forbes, G.S.: Lightning studies using LDAR and companion data sets. 1994 Research Reports, NASA/ASEE Summer Faculty Fellowship Program (L.A. Anderson, E.R. Hosler, W.Camp, eds.), NASA CR-197448, pp. 205-233.
8. Holle, R.L., A.I. Watson, R.E. Lopez, R. Ortiz: Meteorological aspects of cloud-to-ground lightning in the Kennedy Space Center region. Preprints, 26th AIAA Aerospace Sci. Meeting, Reno, NV, 1988, 12pp.