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Lightning Detection for an Air Force
Automated Observation System

HENRY ALBERT BROWN



8 June 1988

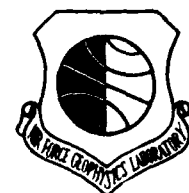


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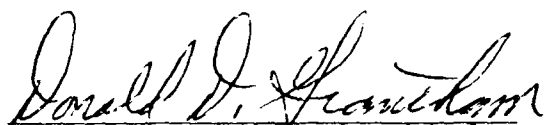


ATMOSPHERIC SCIENCES DIVISION PROJECT 2688
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731

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The Air Force Geophysics Laboratory is conducting an advanced research and development program to develop sensors and techniques to be used in an automated weather observation system. This report concentrates on the progress and plans to automate the observation of one particular weather element: lightning. Since July 1986, AFGL has archived lightning data from the SUNY-Albany Lightning Detection Network (LDN) for the northeastern United States. In an attempt to demonstrate the potential of a commercially-available Remote Display Processor (RDP) coupled with the LDN, a detailed case study was made of a storm that occurred on 10-11 August 1986. The capabilities of the RDP to display the location, motion, and evolution of cloud-to-ground lightning-strike clusters are shown. In addition, some products are shown of software that was developed to track individual lightning-strike clusters, generate their mean position, compute their velocity and maintain a count of strikes per cluster. To illustrate the use of the lightning detection network for observing, we compared network reports and those made by observer. Based on the results, it is apparent that the lightning detection system has great potential as an operational tool for the meteorologist.					
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Lightning Detection for an Air Force Automated Observation System

1. INTRODUCTION

The Air Force Geophysics Laboratory (AFGL) has undertaken a program, in response to HQ USAF Program Management Directive 1017/PE63707F, that will address the required operational capability (Air Force Communications Command Required Operational Capability 801-77) to sense local aviation weather conditions automatically. This program, identified as the Automated Observation System (AOS), is a subset of a larger effort, the Automated Weather Distribution System (AWDS), to achieve operational capability to collect, store, disseminate, and display aviation weather observations and notices.

The current system for weather observation and display is manpower-intensive, and slow to react to rapidly changing weather conditions. State-of-the-art techniques are available that can be applied to the surface weather observation, thus reducing the need for human participation in the process. This report will concentrate on the AOS program and relate AFGL's progress and plans to automate the observation of one particular weather variable: lightning.

1.1 Air Force Lightning Observation Requirements

The Air Weather Service has defined the following lightning observation requirements for support to Department of Defense agencies.

(Received for Publication 31 May 1988)

- a. For resource protection: (1) A real-time display of the location of all cloud-to-ground lightning strikes within 200 miles, (2) Position accuracy of 1/2 mile inside 25 miles, and 1 mile from 25 to 200 miles, (3) Color coded time display, and the ability to compute the direction of movement and time of arrival of a lightning-producing system within a 25, 20, 10, 5, and 3-mile radius of the installation, and (4) An audible warning device that activates when lightning occurs within a preset range.
- b. For flying safety and strategic and defensive applications: A real-time display of all lightning activity (cloud-to-ground, -to-cloud, -to-air, and intra-cloud) with the same range, accuracy, and display requirements cited in a.
- c. For research applications: A data base from which lightning climatologies can be developed. The data should include time, location (latitude/longitude), types and number of strikes.

2. LIGHTNING SYSTEMS

An operational comparison of six lightning warning systems was carried out in 1979 as a result of lightning-induced premature explosions in open-pit mining operations.¹ The commercial devices consisted of a series counter, a corona point, a radioactive probe, a field mill, an azimuth/range locator and a triangulation (direction finder-DF) locator.² The tests were conducted at three sites that had dissimilar thunderstorm regimes. Evaluation parameters of advance-warning-time, time-to-clear-after-the-hazard, alarm-reliability, and false-alarm and failure-to-alarm probabilities were used with a station verification range of 10 nautical miles. The best performance was achieved by the direction-finder locator system. A concern was expressed, however, at its failure-to-alarm rate of 6 to 9 percent.

2.1 Direction Finding Technique

A number of lightning networks that utilize direction-finding (DF) sensors are now operational in the United States and Canada. In fact, a recent map drawn by Lightning Location and Protection, Inc. (LLP) of Tucson shows that more than one-half the area of the United States, Canada and Alaska is under surveillance with LLP networks. The networks exist primarily to provide forest fire warnings; to provide information to power companies for use in operations; and, to provide data for severe storm research.

An LLP lightning network consists of two or more DF sensors. Each DF senses the electromagnetic fields radiated by lightning on two orthogonal magnetic loop-antennas and on a

-
1. Johnson, R.L., Janota, D.E., and Hay, J.E. (1982) An operational comparison of lightning warning systems, *J. Appl. Meteorol.* **21**:703-707.
 2. Krider, E.P., Noggle, R.C., and Uman, M.A. (1976) A gated wideband magnetic direction finder for lightning return strokes, *J. Appl. Meteorol.* **15**:301-306.

flatplate electric antenna. The antennas are wide-band (about 1 kHz to 1 MHz) and the direction of a flash is determined from the ratio of the signals received on the two loop antennas. The DF is designed to respond only to cloud-to-ground (C-G) strikes and to determine the azimuth angle of the strike at a point about 100 to 200 meters above the ground. Each DF transmits a lightning azimuth angle and other information about the strike through a dedicated communication link to a computer, or position analyzer (PA). The analyzer receives the data and calculates, by triangulation, the lightning location. Data-checking and/or optimization techniques may be applied at this time also.³ The PA then sends the final strike position in near real-time to an archival and/or data display device. More detailed discussions of the DF system have been given in other studies.^{4,5}

The accuracy and detection efficiency of lightning systems are of great concern to potential users. At least four factors have been cited⁵ as critical for accuracy: (1) the accuracy of the individual DF antenna alignment; (2) random errors in the angles to the ground-strike points; (3) the category of systematic angle, or "site" errors that are associated with the quality of a DF site location; (4) the location of the strike with respect to the DF.

The detection efficiency, defined as the ratio of the cloud-to-ground strikes detected to the strikes observed, is generally a function of the range and strike magnitude. Strikes of large magnitude will be detected at greater distances by a DF than strikes of small magnitude. At the same time, a DF may miss a close strike because its electronics are saturated. An advantage of a network system is the fact that other DFs may detect that strike. Detection efficiencies on the order of 80 to 90 percent have been cited⁵ in the 10 to 60 nm interval, decreasing to less than 50 percent beyond 200 nm.

2.2 Time-of-Arrival Technique

A second operational system for detecting cloud-to-ground lightning strikes uses a time-of-arrival technique.⁶ The system (Lightning Positioning and Tracking System - LPATS) uses, as a time discrimination base, the LORAN-C navigation network consisting of three or more monitoring stations separated by about 80 nmi. Each station contains two simple whip antennas. One antenna receives the LORAN-C signals, while the other monitors the electric field. In addition, the station contains a timing-signal generator that is synchronized with the generators at the other stations. All stations are connected by a communication link to a central processor. A critical element of the time-

-
3. Hiscox, W.L., Krider, E.P., Pifer, A.E., and Uman, M.A. (1984) A Systematic Method for Identifying and Correcting "Site Errors" in *A Network of Magnetic Direction Finders*, International Aerospace and Ground Conference on Lightning and Static Electricity, Orlando, FL.
 4. Krider, E.P., Noggle, R.C., Pifer, A.E., and Vance, D.L. (1980) Lightning direction-finding systems for forest fire detection, *Bull. Amer. Meteorol. Soc.* **61**:980-986.
 5. Maier, M.W., Binford, R.C., Byerly, L.G., Krider, E.P., Pifer, A.E., and Uman, M.A. (1983) Locating cloud-to-ground lightning with wideband magnetic direction finders, Fifth Symposium on Meteorological Observations and Instrumentation, Toronto, Ont., Canada.
 6. Bent, R.B., Casper, P.W., Scheffler, T.H., and Leep, R. (1983) A unique time of arrival technique for accurately locating lightning over large areas, Proceedings of the Fifth Symposium on Meteorological Observations and Instrumentation, Toronto, Canada, pp. 505-511.

of-arrival technique is clock-synchronization. When a cloud-to-ground strike occurs, the electromagnetic signal radiated is detected by the monitoring stations and the times-of-arrival are noted relative to the LORAN-C time base. The central processor, after analyzing and processing the data and determining that at least three stations have detected the strike, computes its location using spherical hyperbolic geometry. The strike location is then transmitted in latitude/longitude coordinates to end user.

Validation of the accuracy of the LPATS is not available at this time. Indeed there have been very few validation studies of existing lightning networks, primarily due to the difficulty in obtaining a ground-truth data base. Estimates have been made that the LPATS time-of-arrival system has a detection efficiency of 85 percent near the center of the network.⁷ This detection efficiency is also estimated to fall off very slowly with range. The analysis of the Lightning Location and Protection, Inc., and Lightning Positioning and Tracking systems currently being conducted at the National Severe Storms Laboratory will offer a scientific critique of the two major lightning detection systems.

A recent report⁸ detailed further improvements in the LPATS through the use of redundancy verification techniques and a five-fold improvement in time-clock resolution.

2.3 System Utilized in Report

This report will address the analysis of lightning data collected by a network that used detection sensors manufactured by Lightning Location and Protection, Inc., Tucson, Arizona.^{9,2,5,4}

During the summer of 1986, AFGL acquired a LLP Remote Display Processor (RDP). The RDP's main features are the ability to: (1) display real-time lightning maps on a high-resolution eight-color video; (2) store 25,000 flashes for playback modes or viewing in different map scales; (3) store in (ROM) up to 99 user-specified maps; (4) generate hardcopy color maps of lightning displays; (5) sound an audible alarm for lightning alerts; (6) allow symbol or color selection to indicate time development; (7) permit variable time intervals to be selected to determine more precise time definition; and (8) archive data on a tape cassette deck.

In addition to the RDP located at AFGL, several other similar sets are in operation in the Northeast. One is located at the Air Weather Service Detachment at Griffiss AFB, NY; another at the National Weather Service Office at Albany, NY; and a third at the FAA Control Center at Leesburg, VA.

Following the RDP acquisition, a dedicated phone line was installed connecting the RDP to the nearest point of the SUNY-Albany Lightning Location Detection Network operated by the State

-
7. Lyons, W.A., Bent, R.B., and Highlands, W.H. (1985) Operational uses of data from several lightning position and tracking systems (LPATS), *10th International Aerospace and Ground Conference on Lightning and Static Electricity*, Paris.
 8. Casper, P.W., Bent, R.B., and Highlands, W.H. (1988) The Next Generation Lightning Positioning and Tracking System (LPATS), *Proceedings of the AIAA Conference on Lightning*, Oklahoma City, OK, p. 19.
 9. Krider, E.P. and Noggle, R.C. (1975) Broadband antenna systems for lightning magnetic fields, *J. Appl. Meteorol.* **14**, (No.2):252-256.

University of New York at Albany.^{10,11} This system uses LLP Direction Finders (DFs) and detects lightning strikes over the eastern third of the nation. The transmission of data in an LLP format, however, is limited to the northeastern United States. Figure 1 illustrates the partial coverage of the SUNY-Albany Lightning Detection Network in the northeast. Sixteen DF locations are shown in the map area. Data archiving of lightning strike locations began on 27 June 1986 at AFGL and has continued to the present. The data base contains the times, latitudes, and longitudes of all cloud-to-ground lightning strikes observed.

Otis ANGB, MA (FMH), Figure 1, was chosen to be the principal point of interest of this report. One of the primary goals of this study is to illustrate the impact of an operational lightning detection system on a base weather station. A secondary reason is the significance of Otis ANGB to AFGL as the site of our Weather Test Facility. Because of the sensors and the numerous towers situated at the facility, it is especially vulnerable to lightning damage. Weather observations are also available on a 24-hr basis and Chatham radar coverage encompasses the western Cape Cod area.

3. LIGHTNING ACTIVITY ON 10 - 11 AUGUST 1986

3.1 Synoptic Situation

The case selected for study in this report occurred on 10 - 11 August 1986. Figures 2a and 2b show the surface and 500-mb contour fields at 1200 UTC, 10 August 1986. A stationary front oriented east-west lies just to the south of Cape Cod. A cold front extends southwest from a broad low pressure area located over Indiana and Illinois. A secondary cold front is approaching from the northwest and is overtaking the initial cold front. At 500 mb a large trough dominates the central United States with the low pressure centered over Hudson Bay. On the afternoon of 10 August, the cold fronts merged and continued to move southeast initiating widespread thunderstorm activity oriented in NE-SW lines parallel to the front. Early in the evening this activity diminished. However, as the warm sector moved into central New York and Pennsylvania a small, but persistent, cluster of lightning strikes appeared in central Pennsylvania. It is from this area that the storms discussed in this report originated.

Figures 3a and 3b depict the synoptic surface and 500 mb maps 24 hrs later, at 1200 UTC, on 11 August. Dominant features are the low pressure in Quebec with a cold front trailing southwest along the eastern seaboard and into the southeastern United States, just ahead of a large high pressure centered over Iowa. The trough at 500 mb has continued its eastward progress and is located over the Great Lakes. Cape Cod is located in the warm sector midway between the warm and the cold front.

-
10. Orville, R.E., Henderson, R.W., and Bosart L.F. (1983) An east coast lightning detection network. *Bull. Amer. Meteorol. Soc.* **64**:1029-1037.
 11. Orville, R.E., Henderson, R.W., Pyle, R.B., Orville, R.E., Jr., and Ewald, C. (1985) The Use of the East Coast Lightning Detection Network in Operational Aviation Meteorology, Proc. Second International Conference on the Aviation Weather System, Amer. Meteor. Soc., Boston, MA.

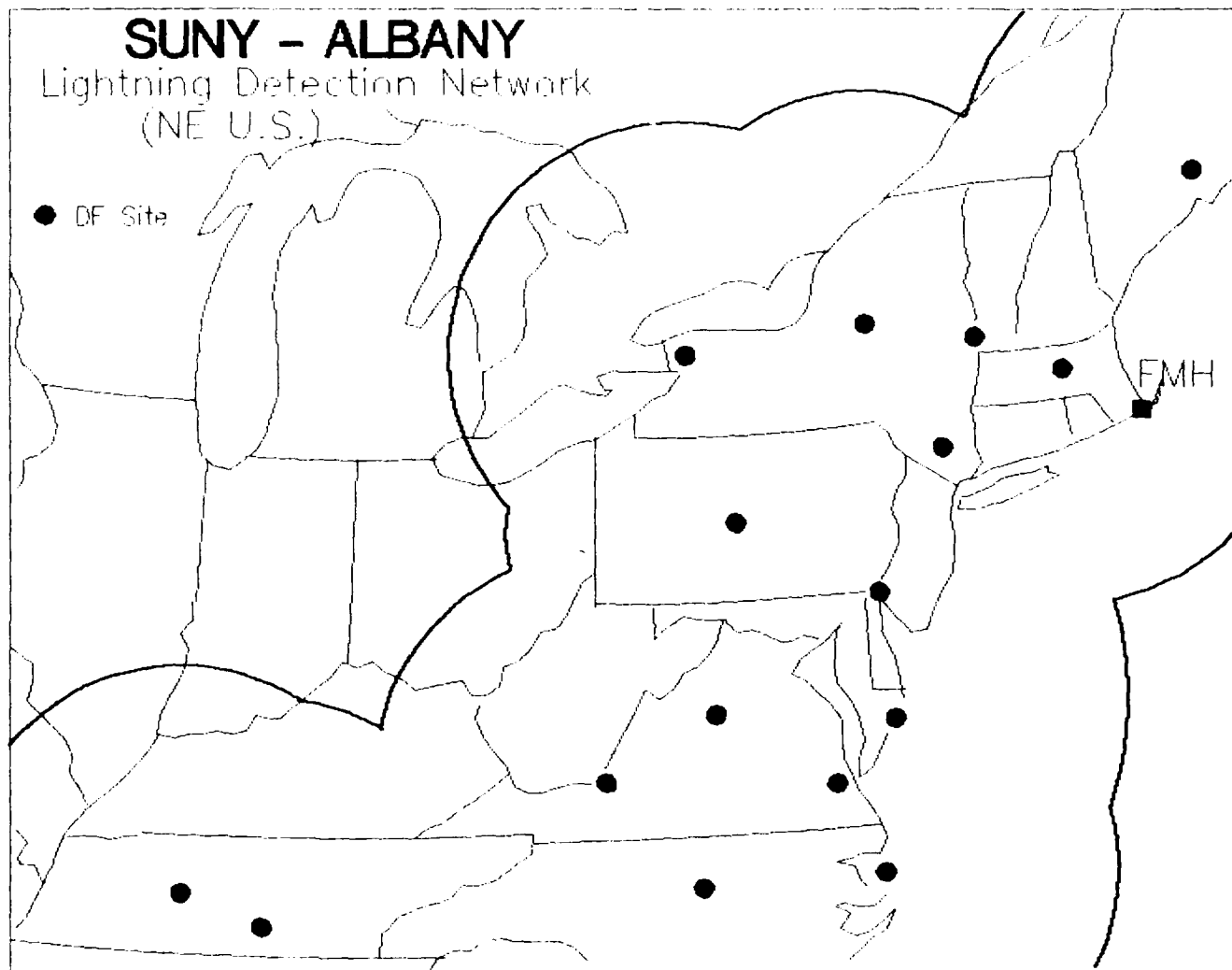
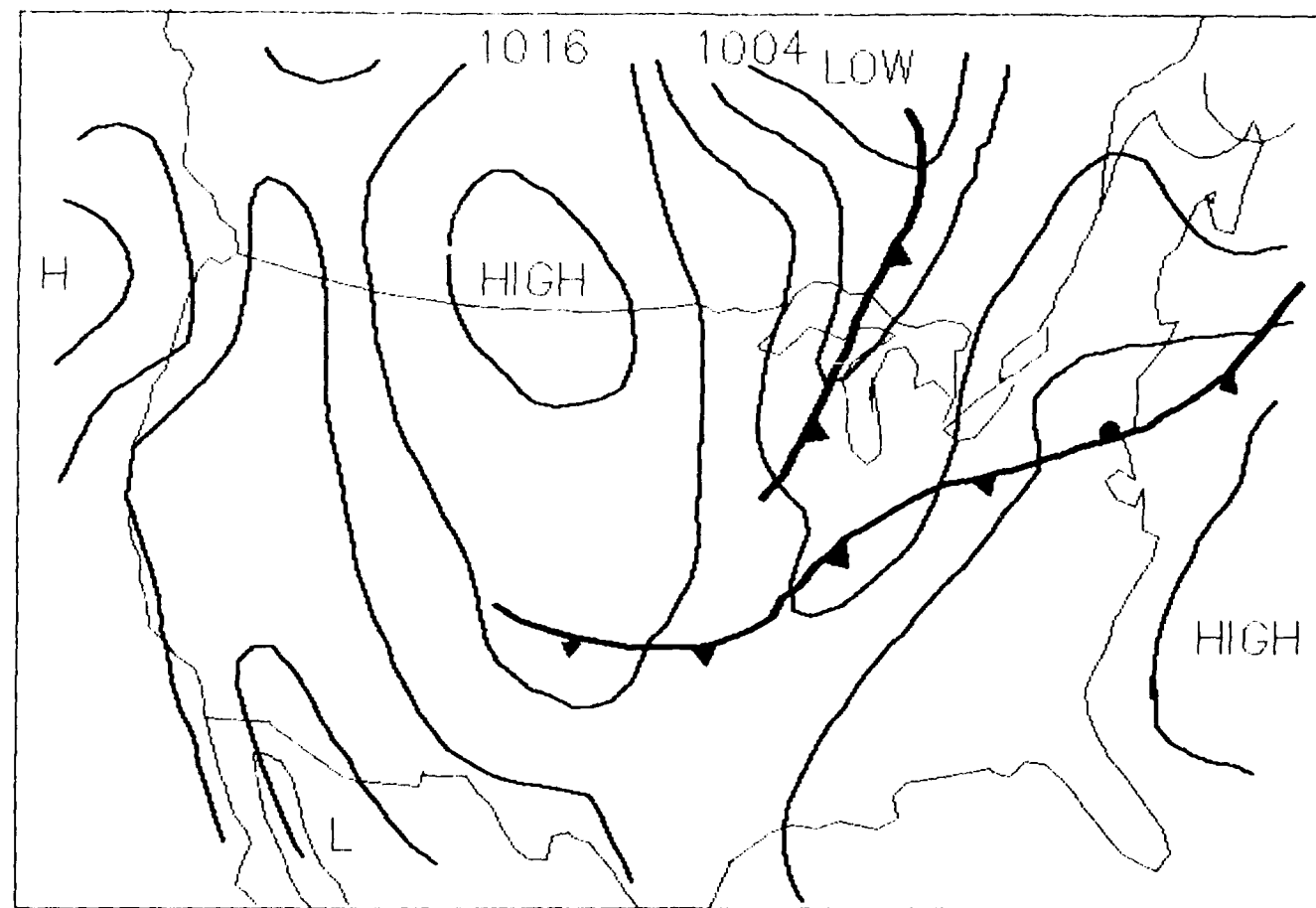


Figure 1. The Northern Half of the SUNY-Albany Lightning Detection Network. Direction Finder (DF) Sites are Denoted by Solid Circles. The Focal Point of the Study, Otis ANGB, MA, is Denoted by the Solid Square and the Call Letters FMH. A Zone of Coverage of 180 nmi Around Each DF Denotes a Boundary of the Network.

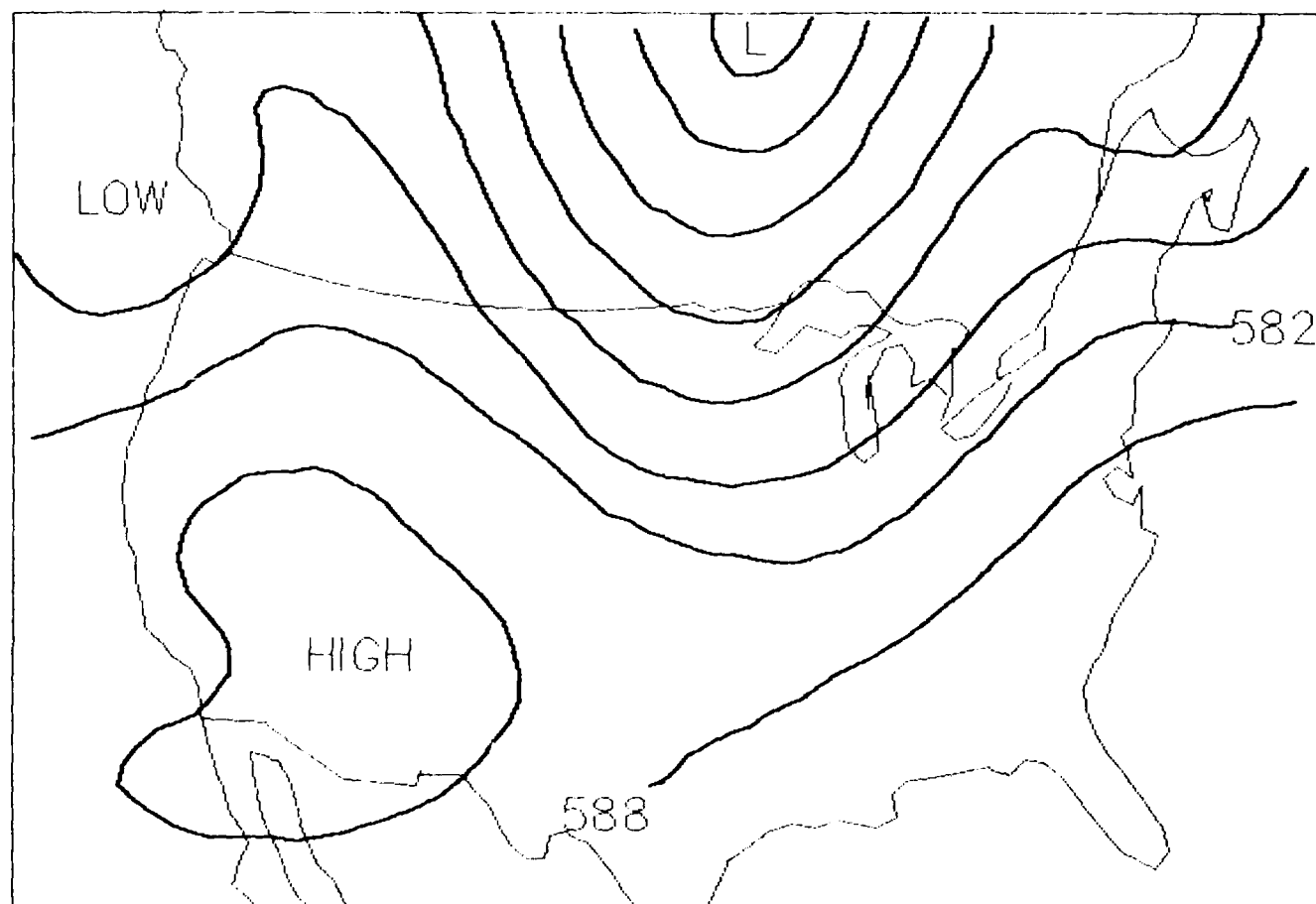
SURFACE WEATHER CHART



AUGUST 10, 1986 - 1200 UTC

Figure 2a. Surface Weather Map for 10 August 1986 at 1200 UTC.

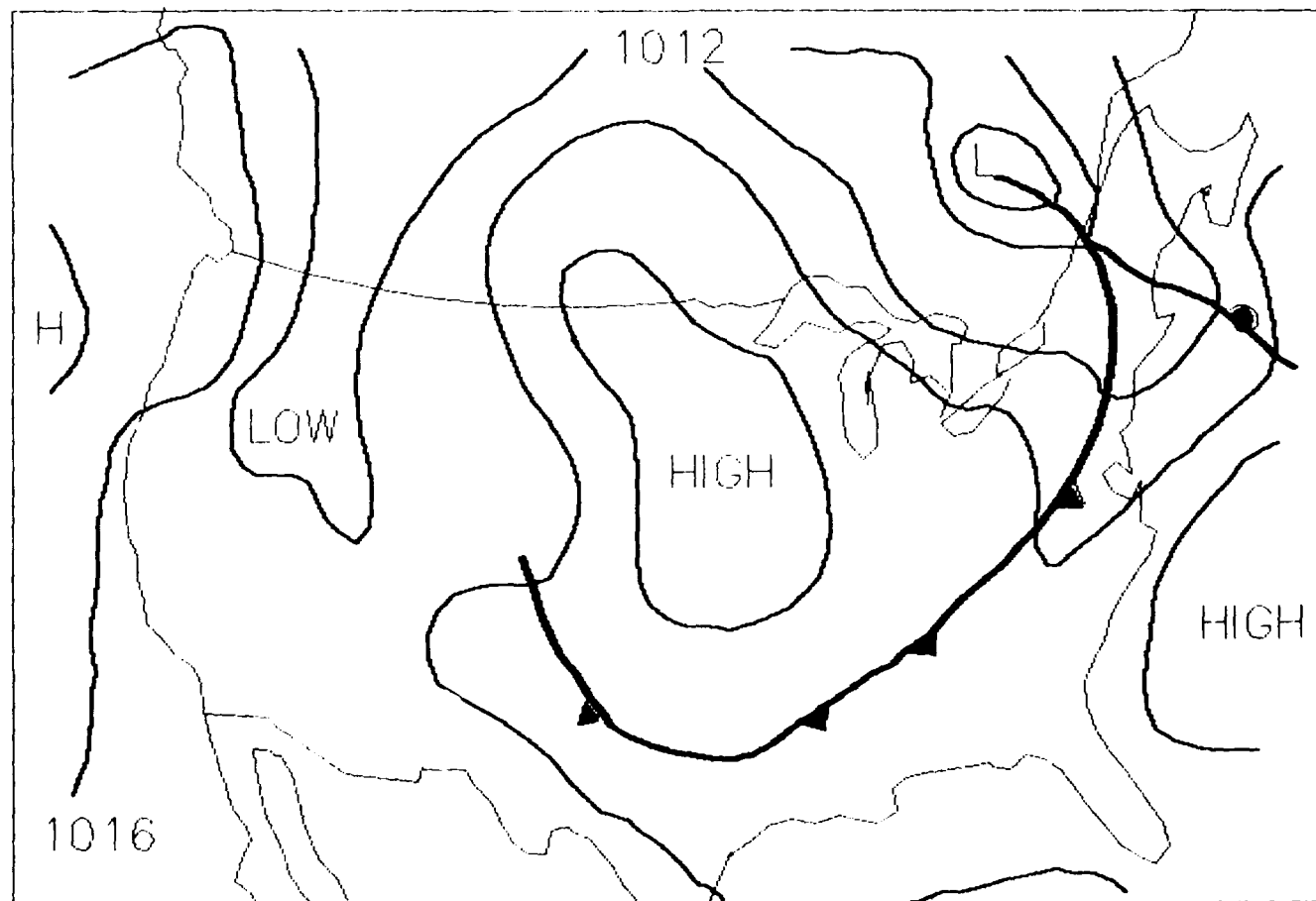
500 -- MILLIBAR CHART



AUGUST 10, 1986 -- 1200 UTC

Figure 2b. 500-mb Chart for 10 August 1986 at 1200 UTC.

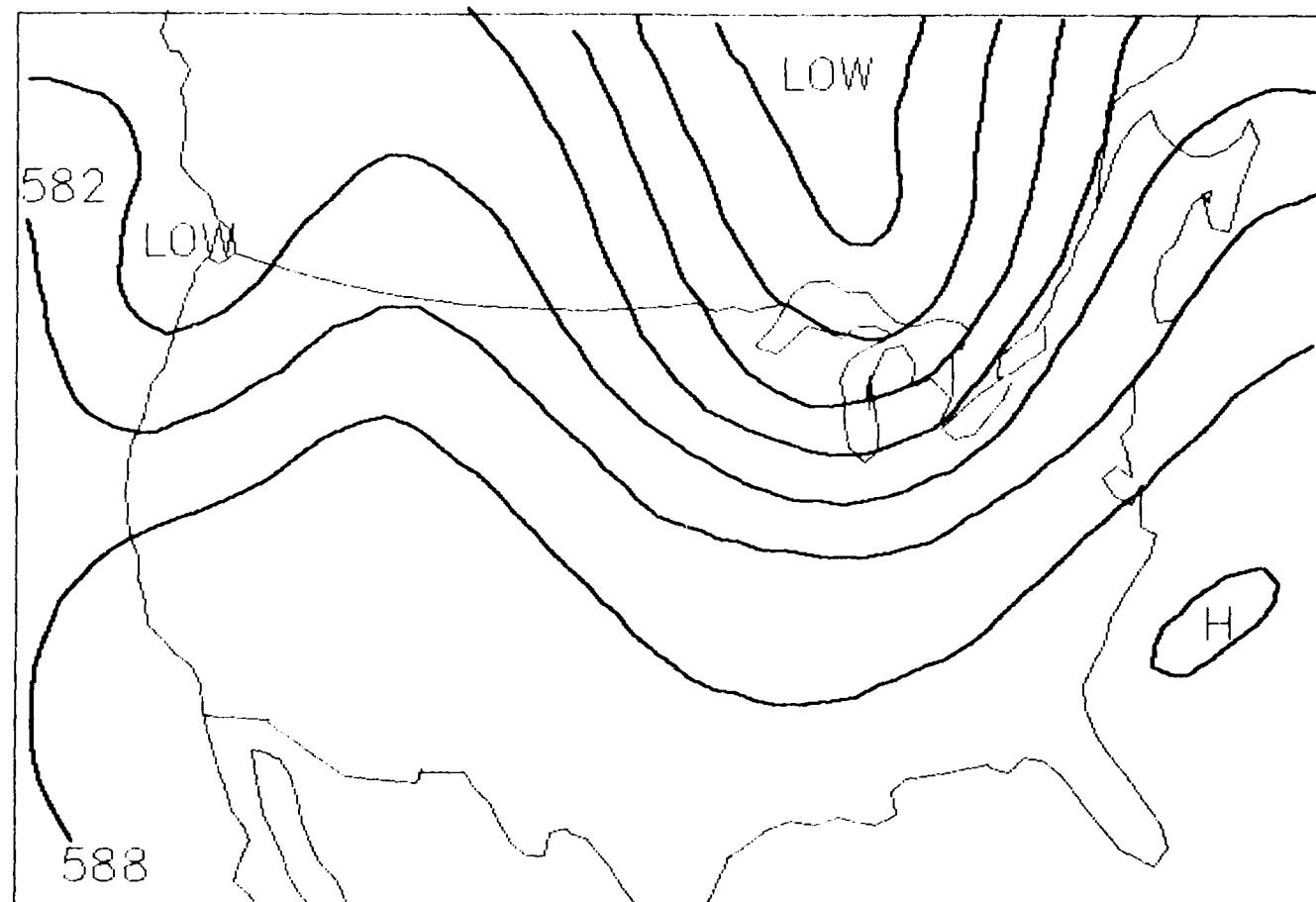
SURFACE WEATHER CHART



AUGUST 11, 1986 – 1200 UTC

Figure 3a. Surface Weather Map for 11 August 1986 at 1200 UTC.

500 — MILLIBAR CHART



AUGUST 11, 1986 — 1200 UTC

Figure 3b. 500-mb Chart for 11 August 1986 at 1200 UTC.

3.2 Hourly Lightning Strike Maps

Figure 4 displays the lightning strike locations for the period 2216 - 2259 UTC, on 10 August. A typical feature of the LLP RDP is an output at the bottom of each map plot with the map number, the time interval of the lightning display, date, flash total for the map, and the color and/or symbols indicating the division of the map display into the selected time intervals. A total of 407 lightning strikes were observed during this period, principally located in storm systems in Pennsylvania and in Virginia.

Figure 5 shows that during the next hour activity increased sharply and moved eastward. The lightning activity appears to be composed of several small clusters oriented NE-SW from eastern Pennsylvania into central Virginia. To determine the number of lightning strikes in the large cluster in eastern Pennsylvania, it would be necessary to have a predetermined map of that size in the ROM. A discussion in the next section cites a need for an option to create a search window in a particular map for more detailed analysis.

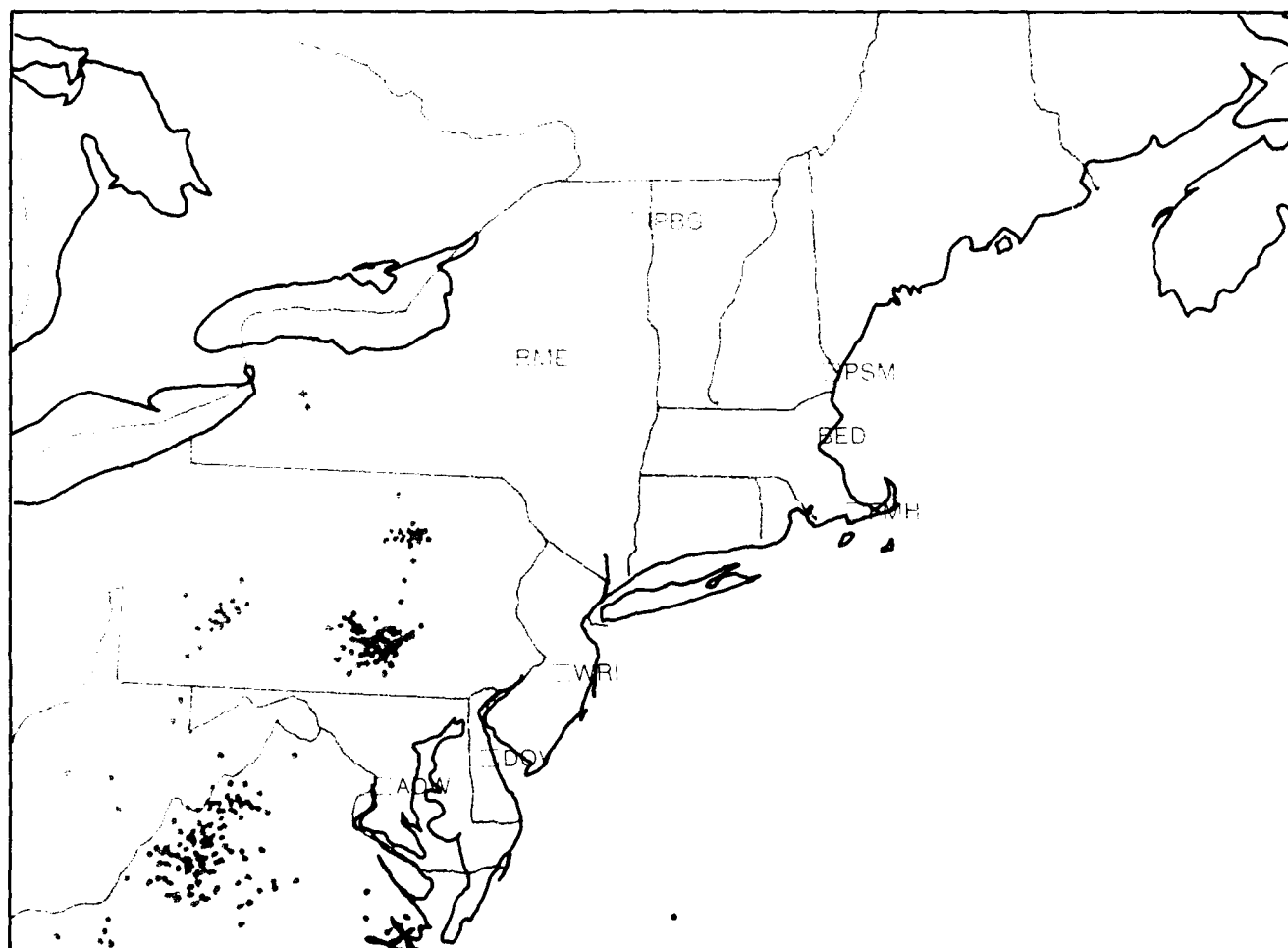
Figures 6 and 7 show continued eastward progression of the lightning systems. By 0200 UTC, Figure 7, activity has almost completely resolved itself into one large cluster of strikes in southeastern Pennsylvania. The lightning activity in Virginia has decreased and the overall level of activity has diminished from 2260 strikes from 00 to 01 GMT to a level of 1559 strikes from 01 to 02 GMT.

Figures 8 to 11 clearly display an east-northeastward progression of the main lightning cluster. Some scattered activity remains in Western Virginia. The areal extent of the lightning cluster has remained fairly constant while the frequency of lightning strikes has decreased and leveled off to about 1200/hour. During the same 4-hr time period, it became apparent that the storm was posing an impending threat to FMH. The storm system generating the lightning activity had been tracked for 7 to 8 hours; it had maintained a level of activity of about 1200 strikes/hour during this period; it now appeared to be on a consistent track to the east-northeast and, barring a sudden dissipation, could arrive at FMH within 4 hours.

Figures 12 to 15 show the continued east-northeast movement of the lightning activity. Between 0600 and 0659 UTC (Figure 12), a separation of the activity into two clusters became apparent. One cluster was centered over southern Connecticut and the other over eastern Long Island.

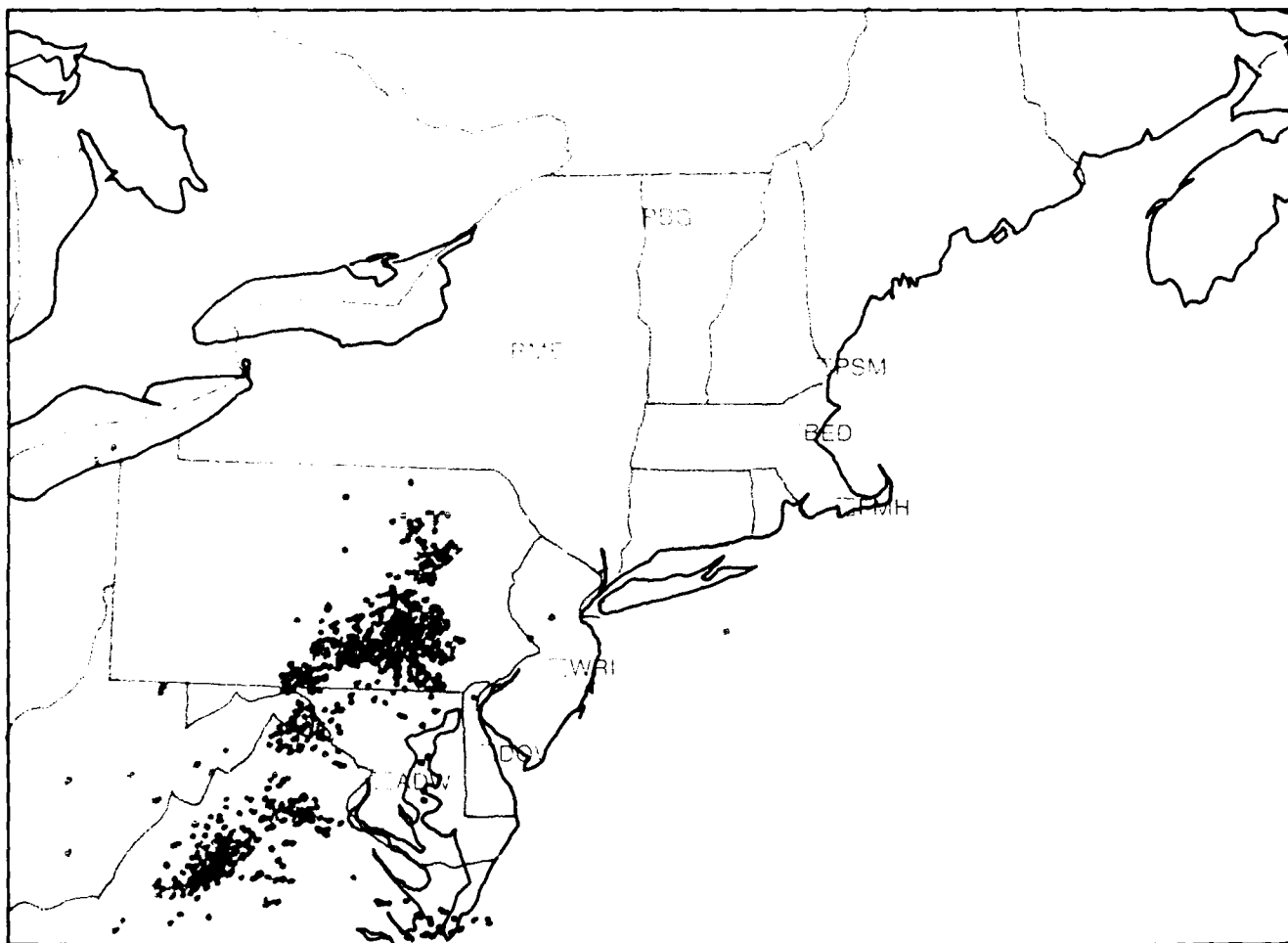
In Figure 13, between 0700 and 0759 UTC, a significant decrease of activity (to 615 strikes/hour) occurred. This decrease appeared to be due to the dissipation of the southern cluster located over Long Island. The northern cluster continued its movement into Rhode Island. Between 0800 and 0900 UTC (Figure 14), the lightning cluster moved almost due eastward from the previous hour and was centered directly over FMH with a strike rate of about 900 flashes/hour. During this period, the AFGL Weather Test Facility's data archival system was disabled and individual instruments suffered considerable lightning damage. The last chart (Figure 15), shows continued eastward progress of the storm and a decrease of activity to about 700 strikes/hour.

Other evidence of the type of activity that occurred during this period was available in the form of the NWS radar reports from Chatham, MA, (CHH). Figure 16 shows an enlarged view of the Cape Cod area with lightning strikes plotted for the period 0800 - 0810 UTC. The range marker centered on FMH is for 30 nmi, the range circle around CHH is for a 50-nmi range. Superimposed on the lightning locations is a plot of the 0807 UTC CHH radar report. Below the figure is the detailed report itself. The



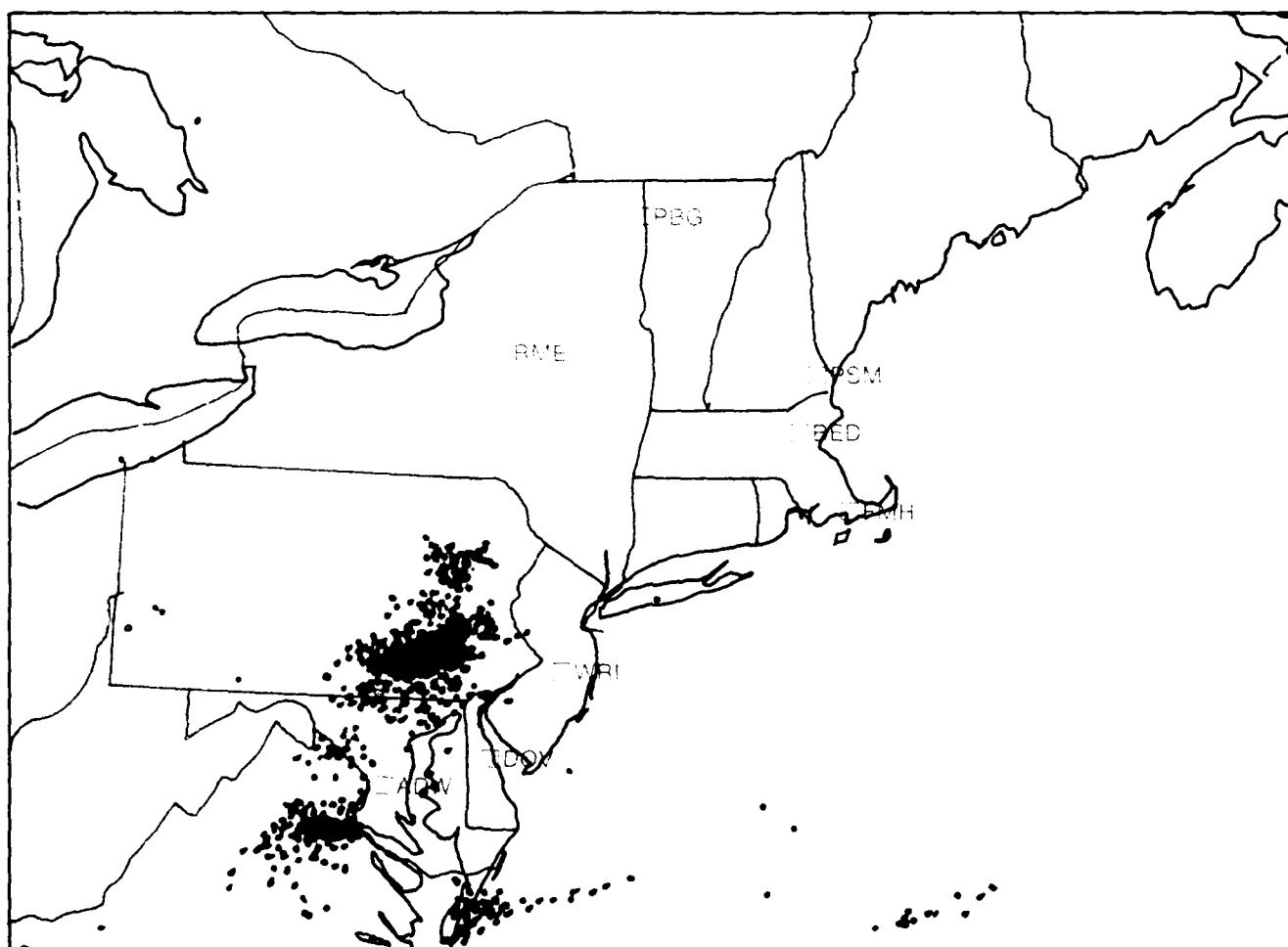
MAP 11 WIDTH= 791 NM 22:16:48 10-AUG-86 TO 22:59:58 10-AUG-86 FLASH TOTAL= 407
 • < - TIME KEY + > +

Figure 4. LLP Lightning Strike Location Chart. The Interval Plotted is Shown at the Bottom of the Chart, 22:16:48 to 22:59:58, with the Date, 10 August 1986, and the Total Number of Strikes Observed, 407. The Time Key Shows the Symbols Selected to Represent Negative and Positive Flashes (Diamond for Negative and Plus for Positive) and are Color-Coded to Represent Time-Intervals Plotted.



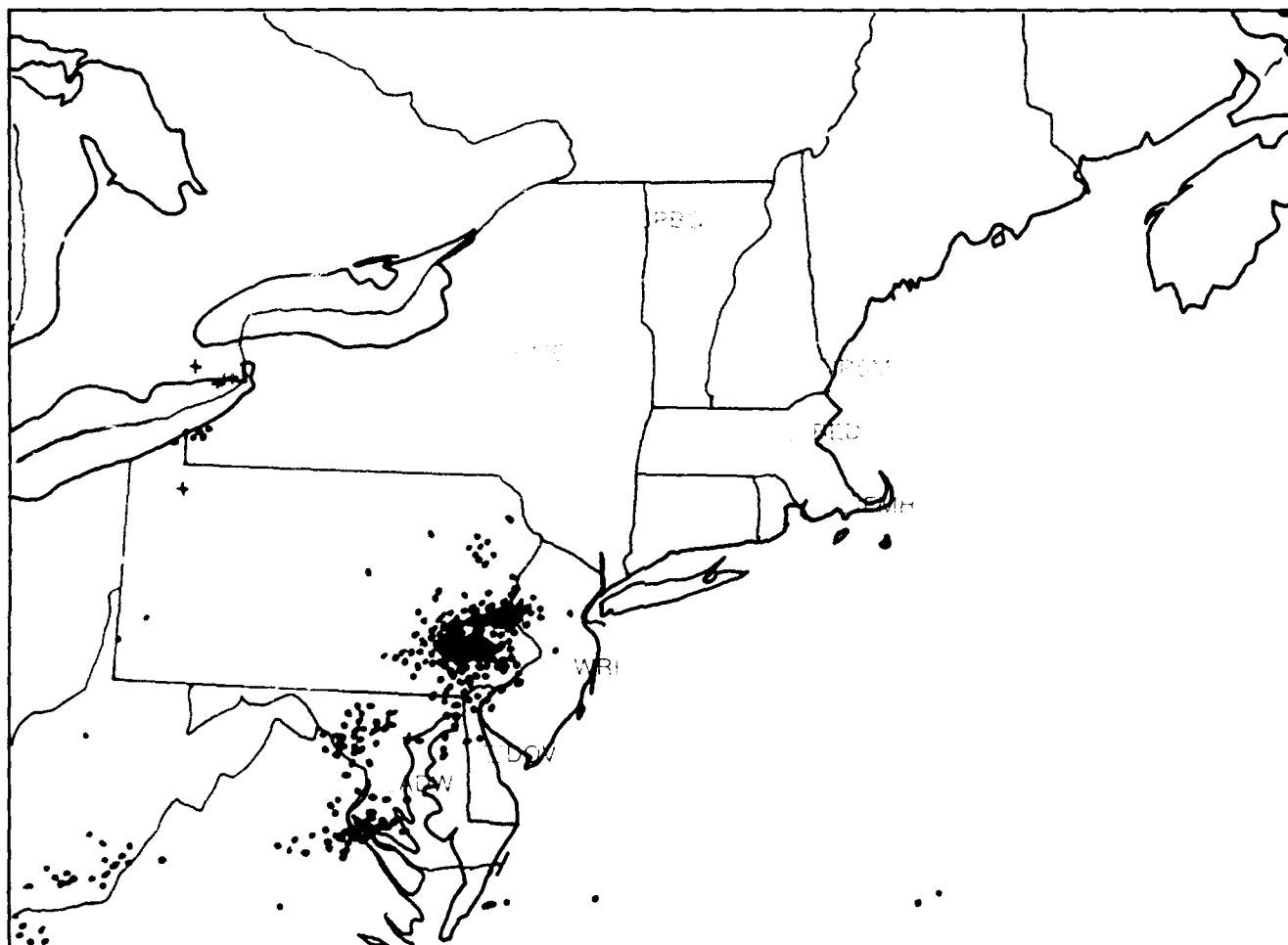
MAP 11 WIDTH = 791 NM 23:00:09 10-AUG-86 TO 23:59:59 10-AUG-86 FLASH TOTAL = 1739
 • < - TIME KEY + > +

Figure 5. LLP Lightning Strike Location Chart for the Period 23:00, 10 August to 00:00 UTC, 11 August 1986.



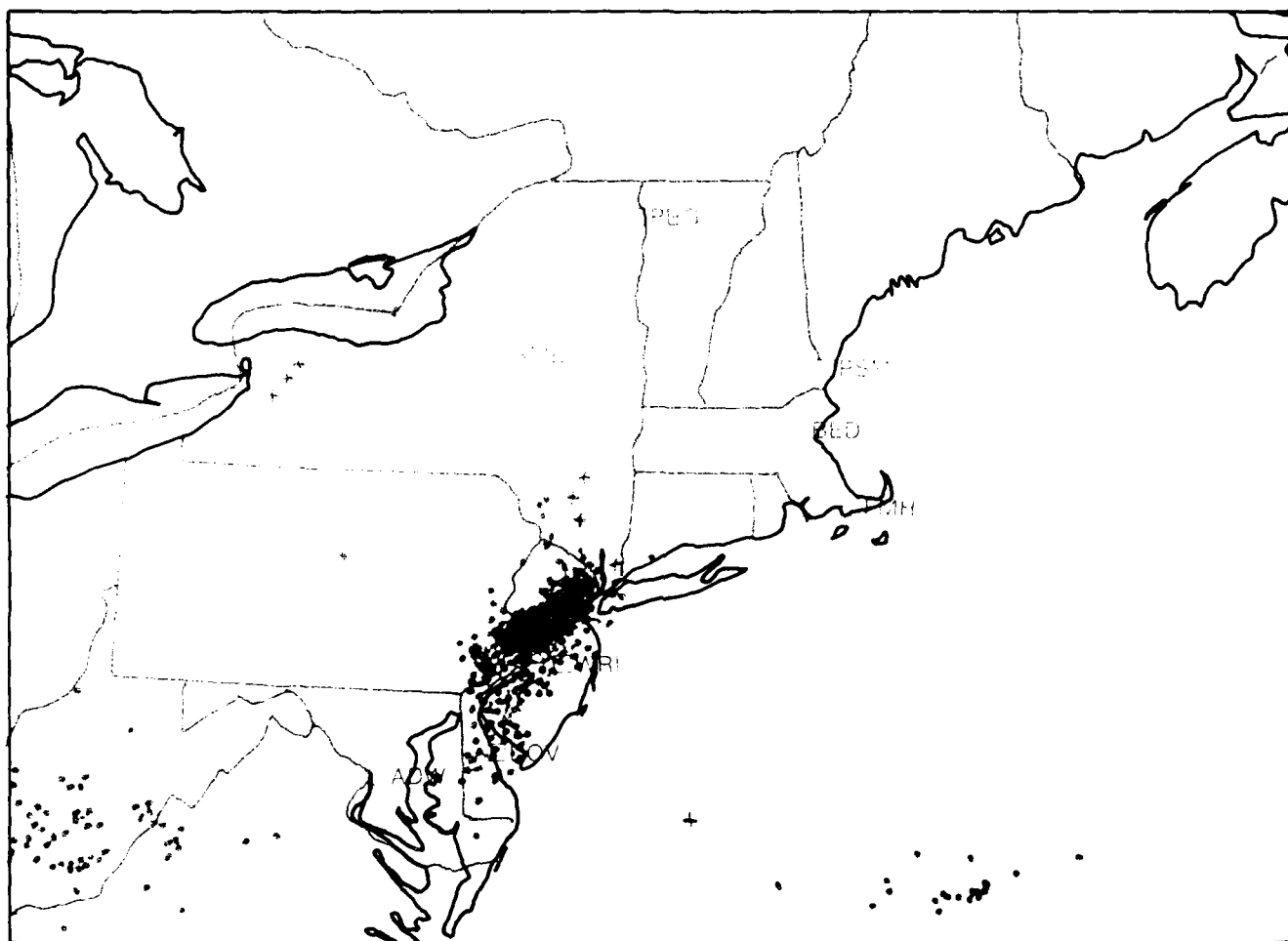
MAP 11 WIDTH= 791 NM 00:00:00 11-AUG-86 TO 00:59:59 11-AUG-86 FLASH TOTAL= 2260
 ● < - TIME KEY + > +

Figure 6. LLP Lightning Strike Location Chart for the Period 00:00 to 01:00 UTC, 11 August 1986.



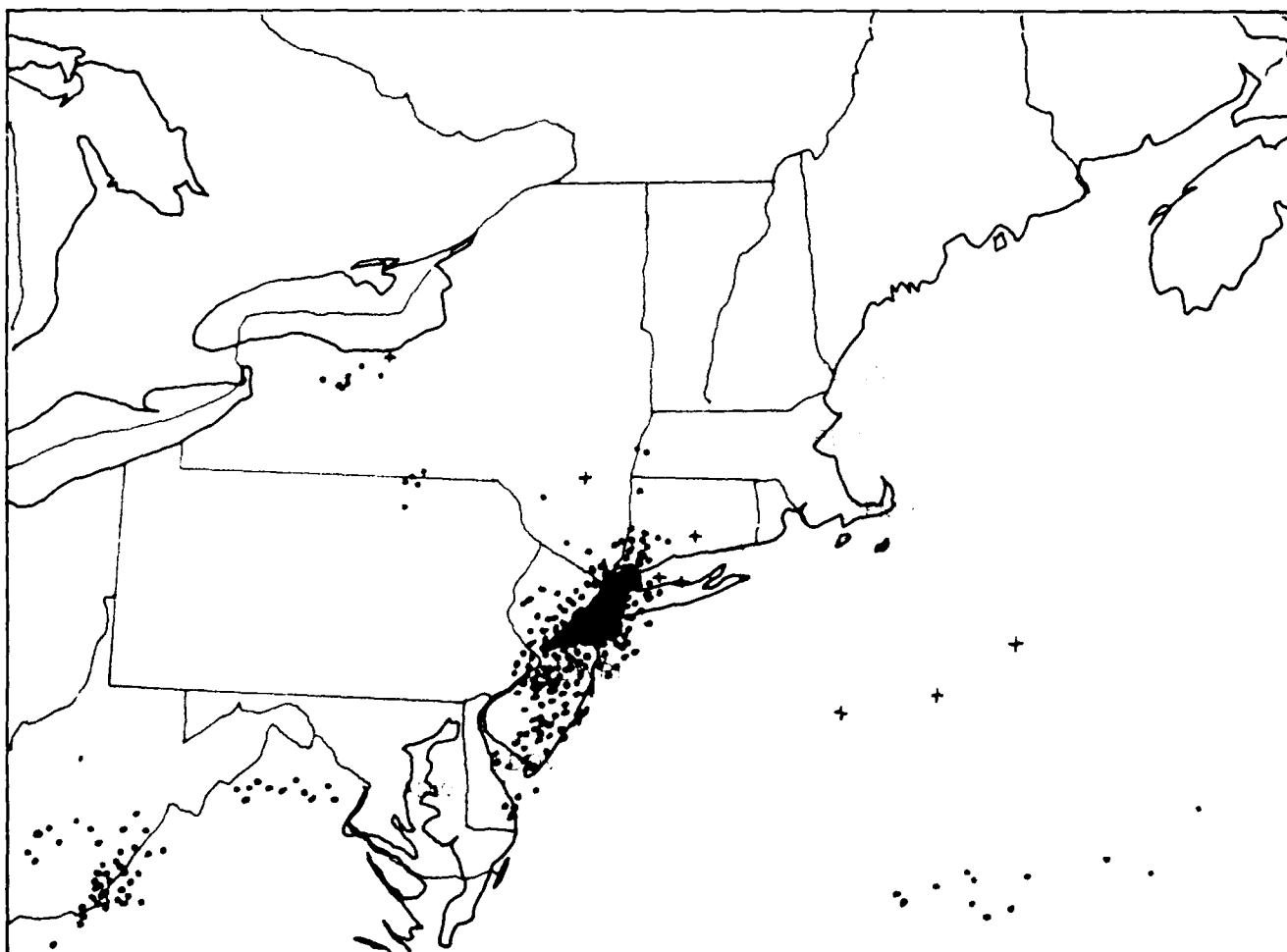
MAP 11 WIDTH = 791 NM 01:00:01 11-AUG-86 TO 01:59:58 11-AUG-86 FLASH TOTAL = 1559
 • < - TIME KEY + > +

Figure 7. LLP Lightning Strike Location Chart for the Period 01:00 to 02:00 UTC, 11 August 1986.



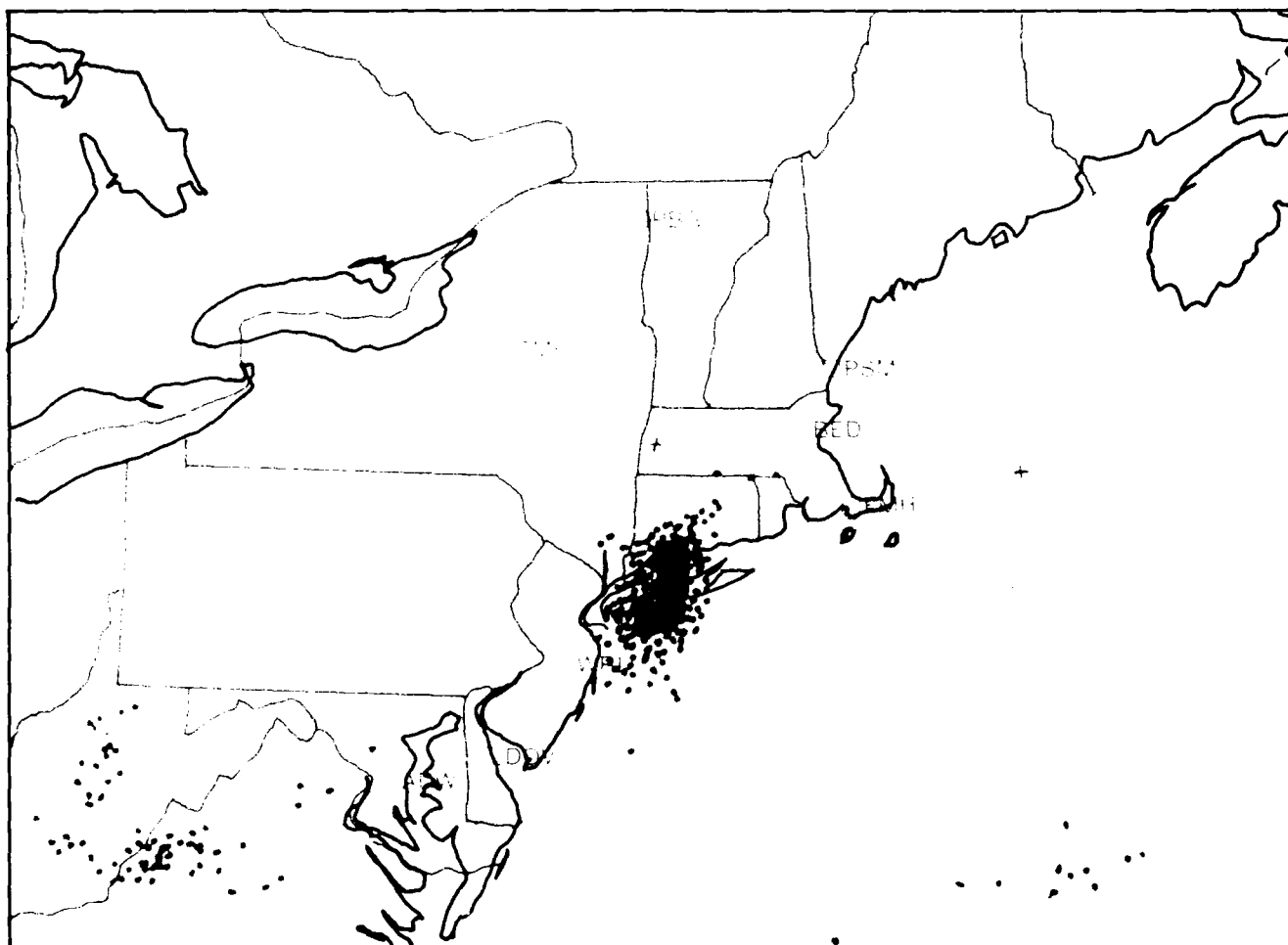
MAP 11 WIDTH= 791 NM 03:00:01 11-AUG-86 TO 03:59:59 11-AUG-86 FLASH TOTAL= 1769
 • < - TIME KEY + > +

Figure 9. LLP Lightning Strike Location Chart for the Period 03:00 to 04:00 UTC, 11 August 1986.



MAP 11 WIDTH = 791 NM 04:00:08 11-AUG-86 TO 04:59:59 11-AUG-86 FLASH TOTAL = 1187
 ● - TIME KEY + + +

Figure 10. LLP Lightning Strike Location Chart for the Period 04:00 to 05:00 UTC, 11 August 1986.



MAP 11 WIDTH = 791 NM 05:00:01 11-AUG-86 TO 05:59:55 11-AUG-86 FLASH TOTAL = 1225
 ● < - TIME KEY + > +

Figure 11. LLP Lightning Strike Location Chart for the Period 05:00 to 06:00 UTC, 11 August 1986.

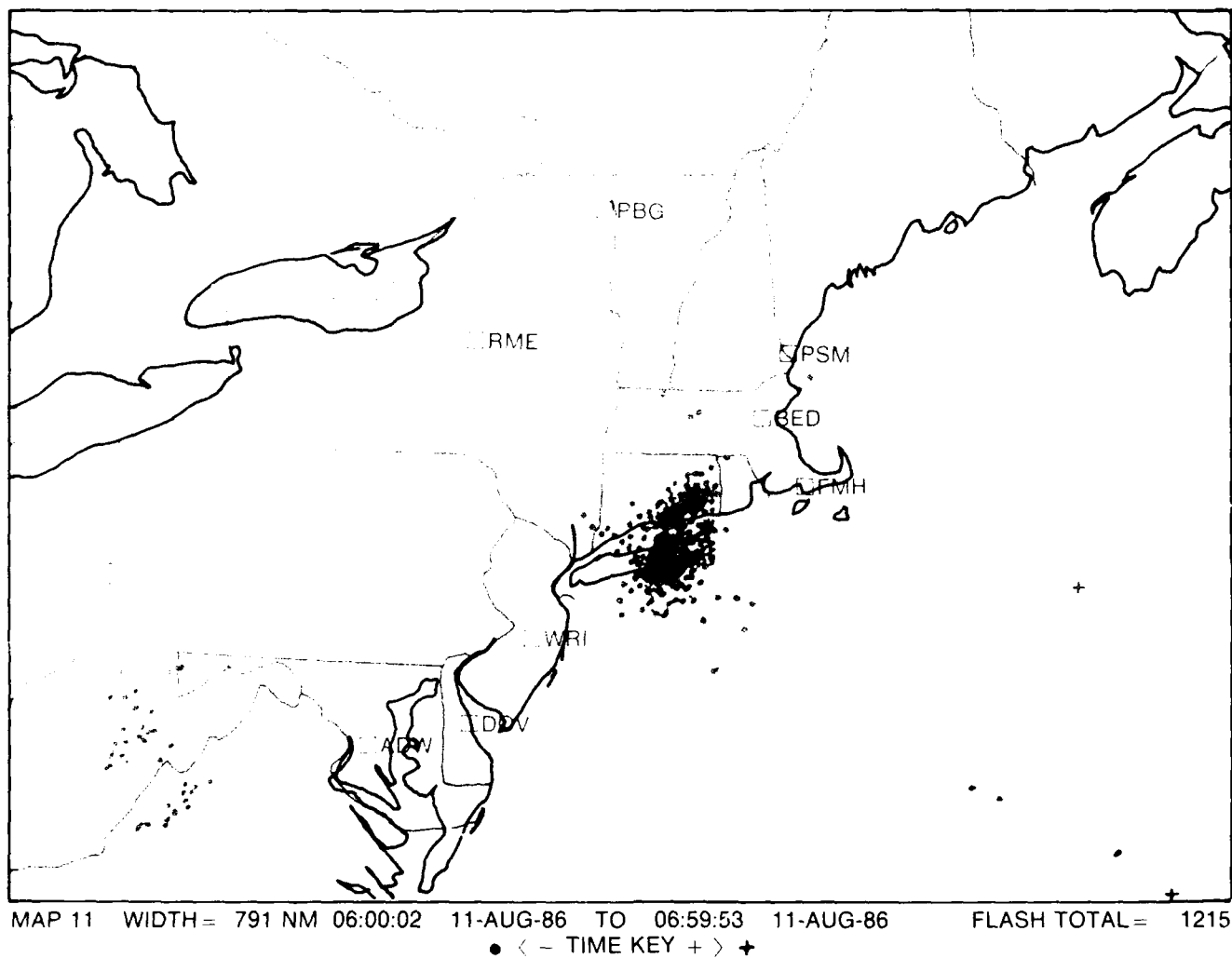
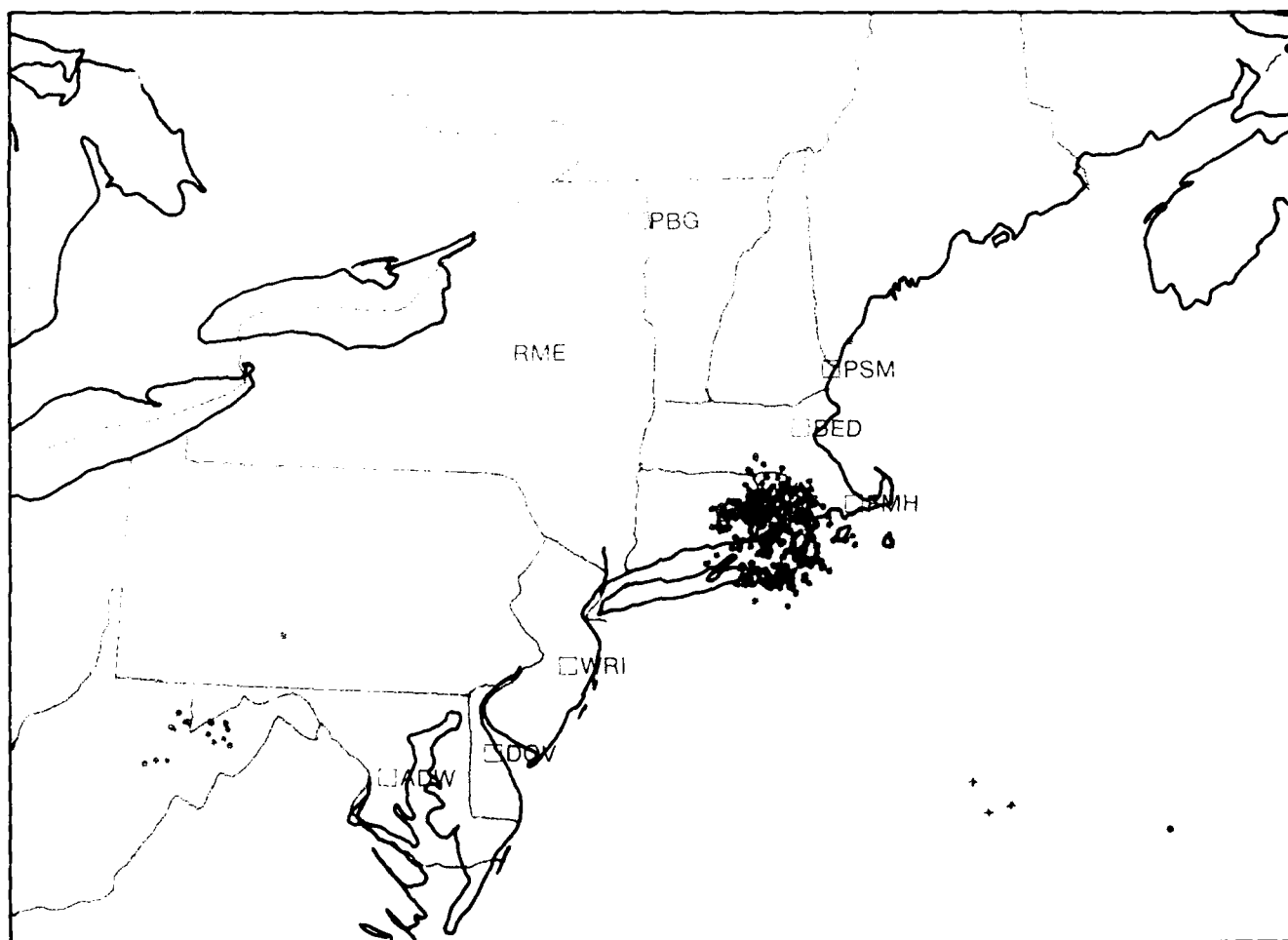
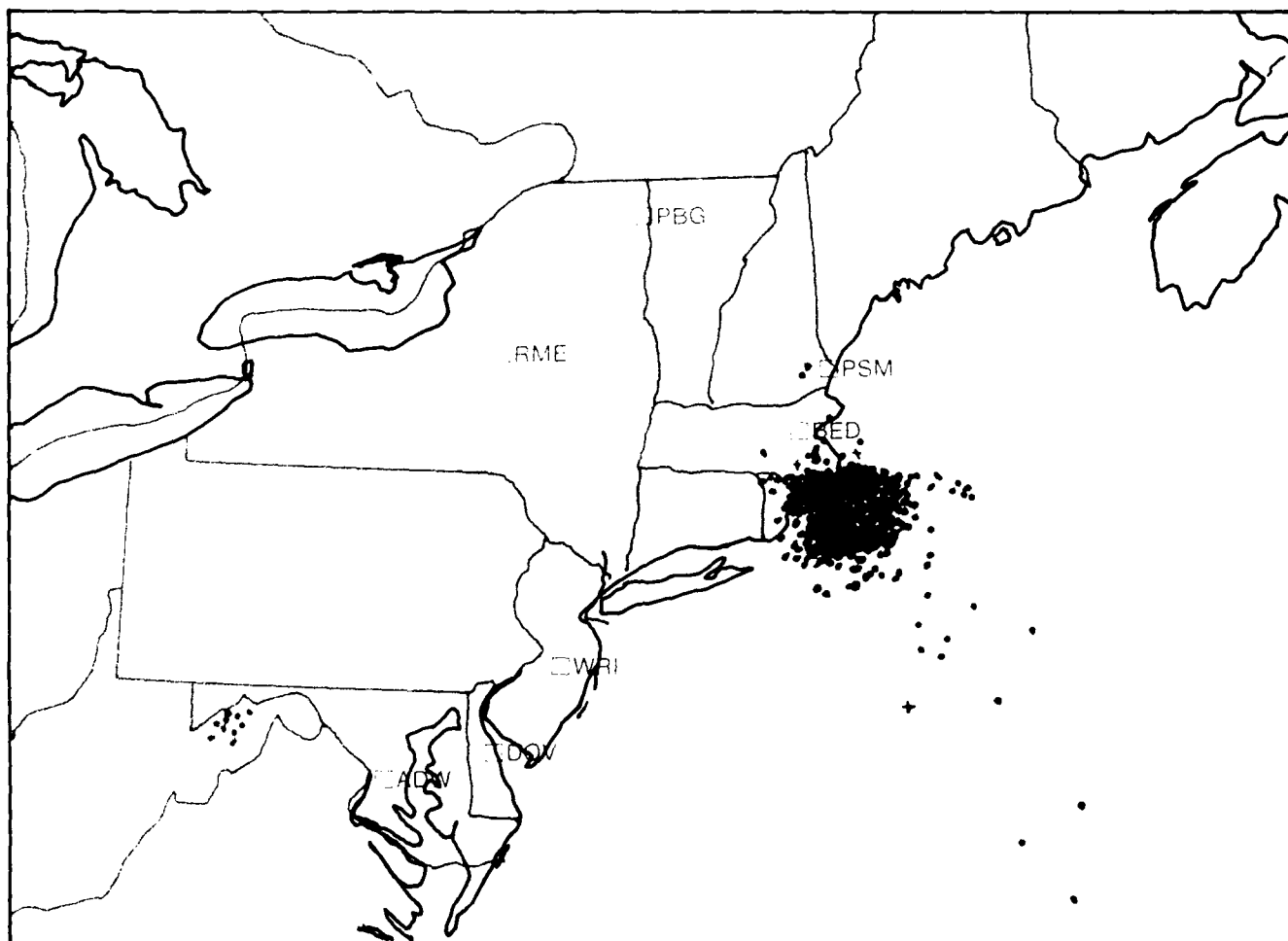


Figure 12. LLP Lightning Strike Location Chart for the Period 06:00 to 07:00 UTC, 11 August 1986.



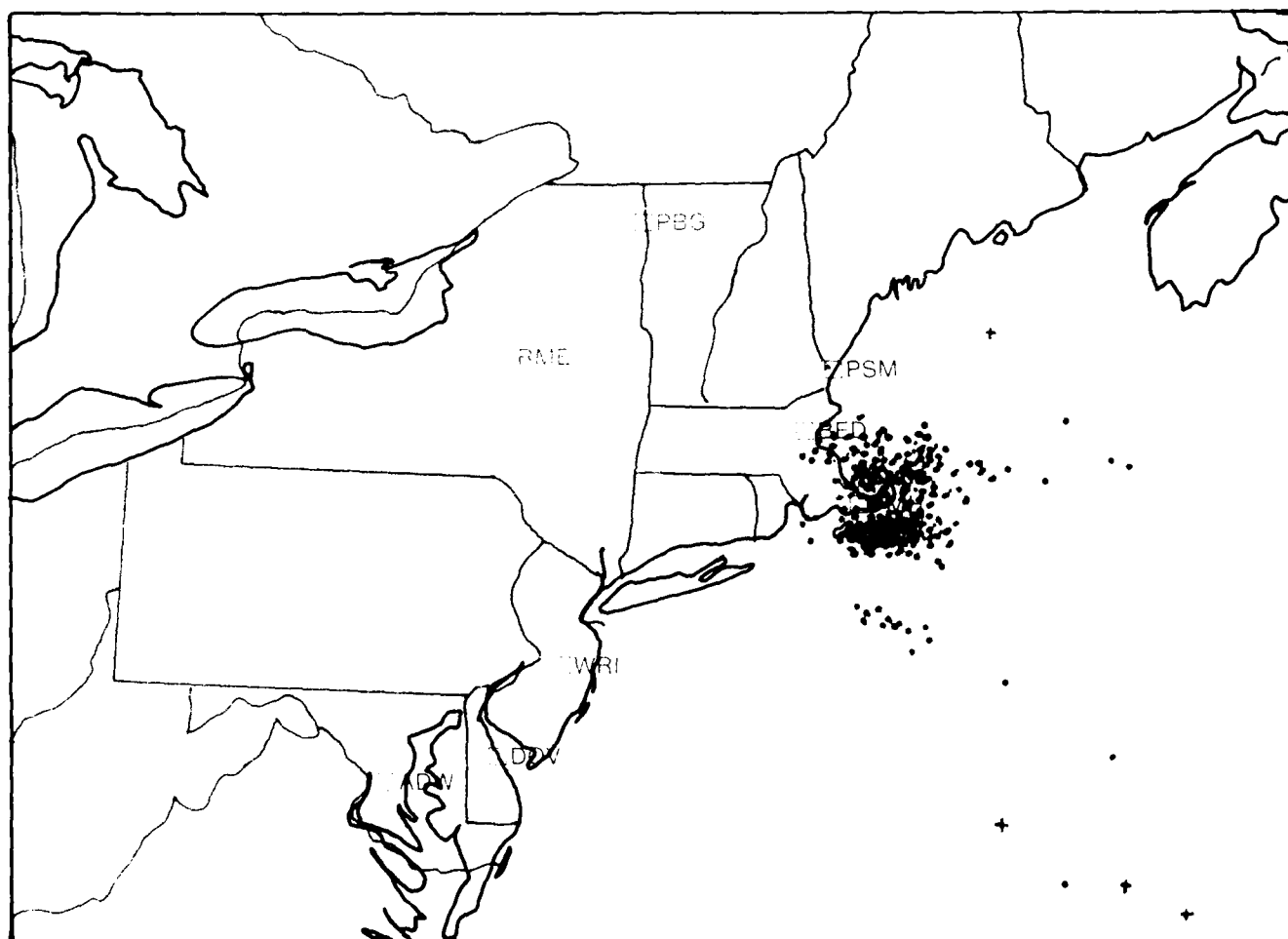
MAP 11 WIDTH= 791 NM 07:00:00 11-AUG-86 TO 07:59:55 11-AUG-86 FLASH TOTAL= 615
 • < - TIME KEY + > •

Figure 13. LLP Lightning Strike Location Chart for the Period 07:00 to 08:00 UTC, 11 August 1986.



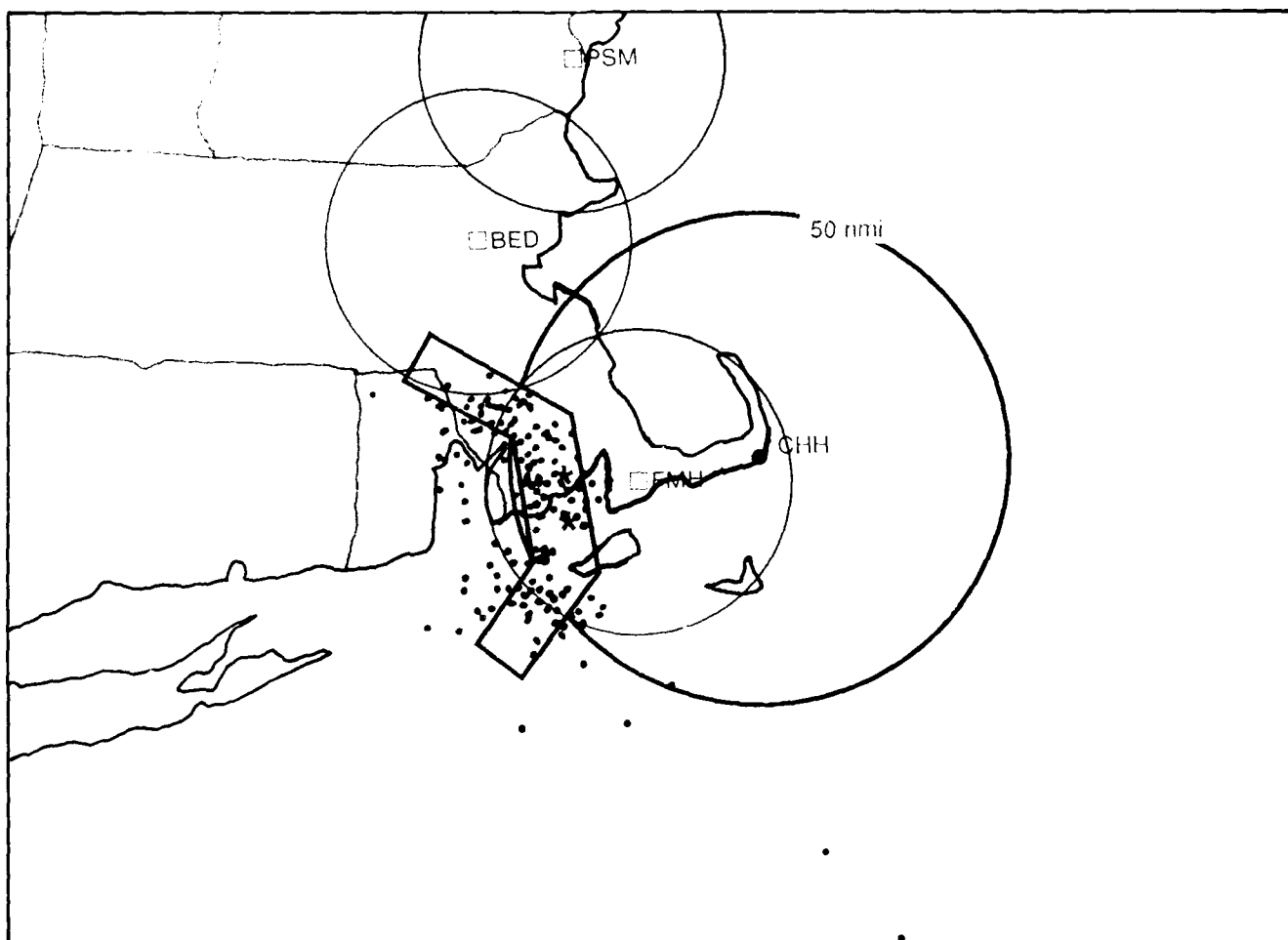
MAP 11 WIDTH = 791 NM 08:00:10 11-AUG-86 TO 08:59:58 11-AUG-86 FLASH TOTAL = 913
 • < - TIME KEY + > +

Figure 14. LLP Lightning Strike Location Chart for the Period 08:00 to 09:00 UTC, 11 August 1986.



MAP 11 WIDTH= 791 NM 09:00:04 11-AUG-86 TO 09:59:59 11-AUG-86 FLASH TOTAL= 736
 ● < - TIME KEY + > +

Figure 15. LLP Lightning Strike Location Chart for the Period 09:00 to 10:00 UTC, 11 August 1986.



MAP 44 WIDTH= 260 NM 08:00:10 11-AUG-86 TO 08:09:56 11-AUG-86 FLASH TOTAL= 163
 ● < - TIME KEY + > +

CHH RADAR 08/11 0807 SLP LN 9TRWXA/NEW 286/70 282/45 243/45 235/65
 10W; CELL MOVEMENT C2430; TOPS 470 @ 274/41; HAIL 266/40 253/41 TROP 449

Figure 16. Composite Lightning Strike Location and Radar Chart. Lightning Strikes are Plotted for the Period, 08:00 to 08:10 UTC, 11 August 1986. The Plotted Radar Report is from Chatham, MA (CHH) for 08:07 UTC, 11 August 1986. The Range Circle Around CHH is 50 nmi. The Complete Radar Report is Given Beneath the Chart.

agreement between the radar and lightning observations is quite good, considering the 10-min duration of the lightning observations. Also available was a pressure trace at Otis (Figure 17), which shows a 2 millibar pressure jump occurring at about the same time as the leading edge of the lightning strikes reached FMH. The trace resembles the characteristic bubble- or meso-high so frequently seen in the Great Plains with squall line passages. The duration of the meso-high pressure field also corresponds roughly to the duration of the thunderstorms at Otis.

One of the more powerful features of the LLP RDP system is the ability to play back data during real-time operation without interrupting data archival. Figure 18 illustrates this option, and the operator can choose to select a time interval for replay. In this case, the period 0200 to 1059 UTC, 11 August 1986 was chosen. A second option offers a choice of time increments for display. In this case, one-hour increments were chosen and six colors are cycled to represent the time intervals. A third option allows the choice of a variety of symbols to represent a lightning strike. In this case, the choice was a small square to represent negative cloud-to-ground strikes and a small plus to represent positive cloud-to-ground strikes. The ability to display a portion of a storm's lifetime in this manner provides an excellent tool to the forecaster in determining the direction, speed, intensity levels, and trends of a storm system. Since the system plots the strikes in chronological order, an animation representation is also achieved. This particular storm was unusual in several ways. It was an isolated, compact, nocturnal storm system that maintained an almost steady-state intensity-level over a 12 to 14 hr period.

3.3 Comparison with Observations

A condensed copy was made of the surface weather observation from the Federal Meteorological Form 1-10 for Otis ANGB and is depicted in Figure 19. The type of observation is listed in the left column, the time of observation is next, followed by the sky condition column. The next five columns are prevailing visibility, weather, wind, altimeter and remarks. Because of fog and reduced visibility, the observer did not report distant lightning until 0755. At 0809 the observer reported a thunderstorm west of the station moving east with frequent lightning in the clouds from the west to the north. At 0821 a special observation noted a heavy rainshower with a thunderstorm overhead moving east and frequent lightning in the clouds, cloud-to-cloud and cloud-to-ground. Later observations noted the decrease in intensity of the showers and that the thunderstorm moved east with the frequency of lightning decreasing at Otis.

In the lower half of Figure 19, the lightning program was used to determine the time a lightning strike was first observed within a specified distance of FMH. This would be equivalent to activating an alarm as various range bins experience a first strike. The tabulated data clearly reveals the erratic motion of lightning strikes and the difficult problem of forecasting the time of occurrence of a strike within specific range intervals. At 0702 the first strike occurred within the 60 nmi range. Twelve minutes later a strike occurred within 50 nmi, followed by seven minutes before a strike occurred within 40 nmi. Then 26 minutes elapsed before a strike occurred within 30 nmi. The next three intervals are of great interest. Nine minutes elapsed before a strike was reported inside the 20 nmi range, followed by 11 minutes passing before a strike occurred within 10 nmi of FMH. Specifically, it

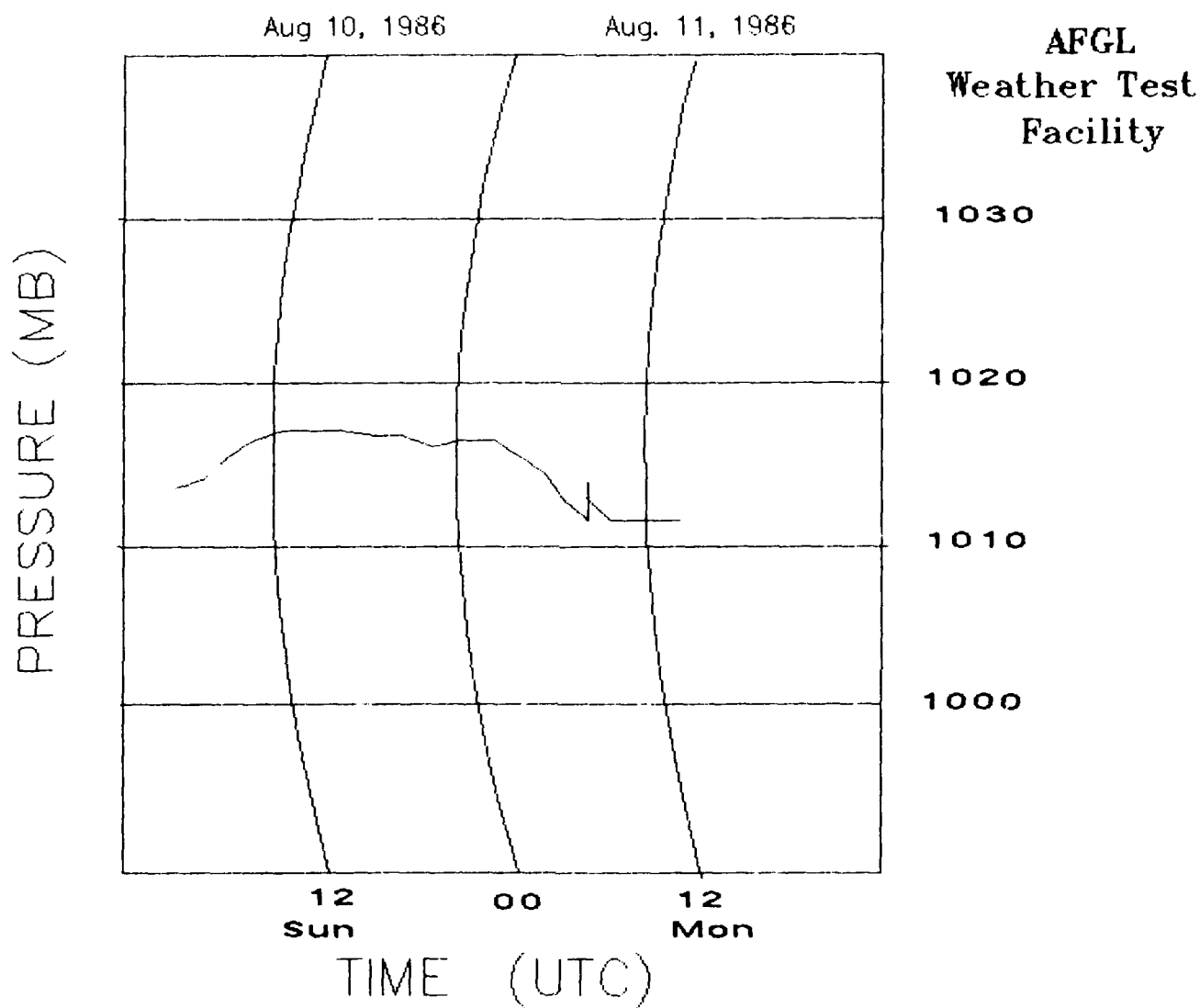


Figure 17. Pressure Trace Reconstructed from the Chart Collected by the AFGL Weather Test Facility at Otis ANGB, MA. The Time Period is for 10-11 August 1986.

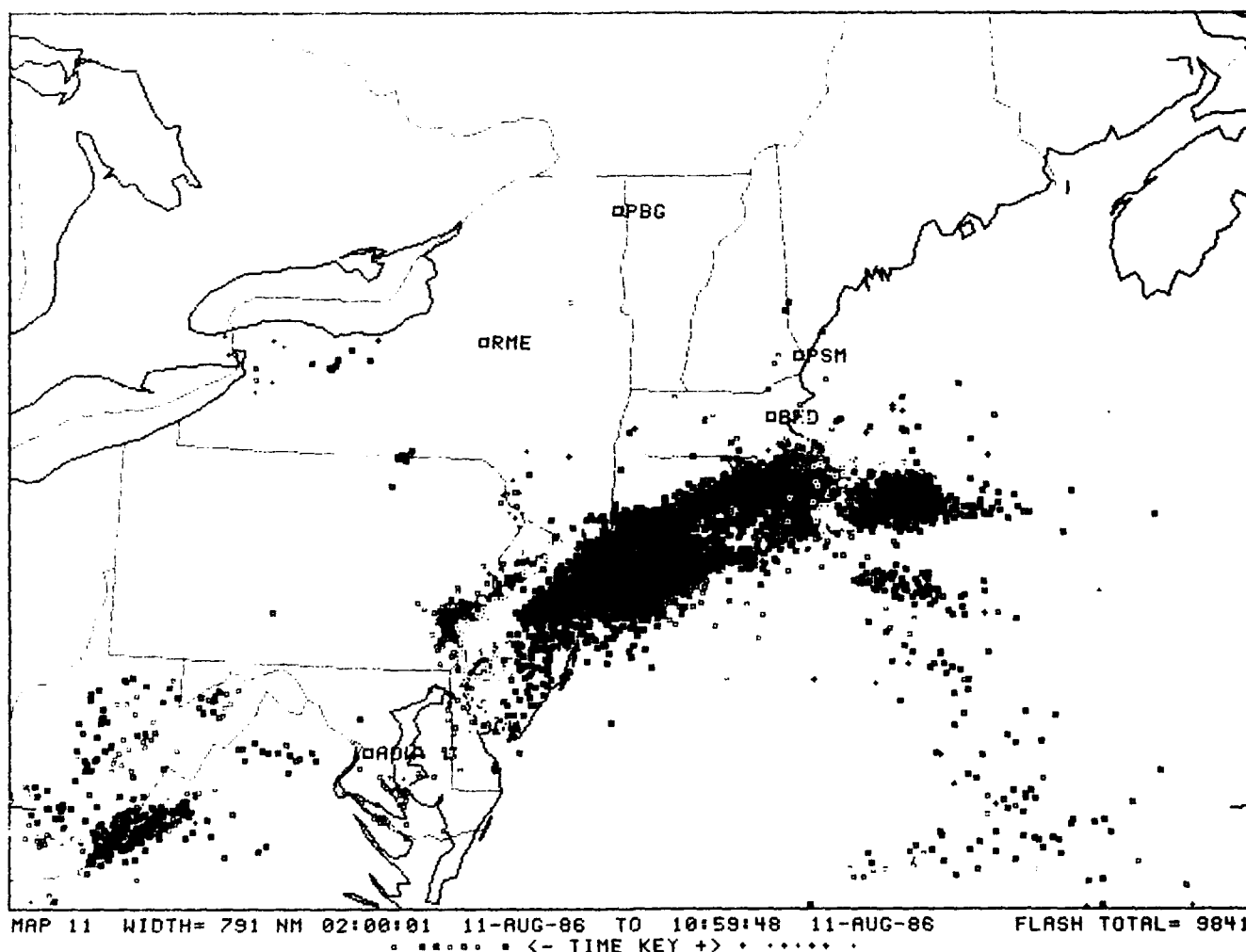


Figure 18. LLP Lightning Strike Location Chart for the Period 02:00 to 11:00 UTC, 11 August 1986. The Nine-Hour Time Period Represents a Major Portion of the Storm's Lifetime. Six Colors Alternate to Represent the Time-Increment Selected. In This Case a One-Hour Increment was Chosen.

SURFACE WEATHER OBSERVATIONS - OTIS ANGB, FALMOUTH, MA

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=====
RS 0555 9 SCT E200 OVC          7          1508 /991/717 1607

SP 0625 M3 BKN 200 OVC          3   F          1606 /989

SP 0634 M2 OVC                  2   F          1504 /989

RS 0655 W1 X                    3/4   F          1608 /987/VSBY LWR S

SP 0713 W1 X                    1   F          1710

RS 0755 M2 OVC                  1 1/2   F          1814 /984/OCNL LTG W - N

SP 0809 M2 OVC                  1 1/2   TF          1808 /984/T W MOVG E FQT LTG IC
                                   W - N

SP 0821 M2 OVC                  1   TRW+F   E2520   G30/T OVHD MOVG E FQT
                                   LTGICCCCG ALQ PRESRR

SP 0838 M12 BKN 30 OVC          5   TRW-F   E2506 /986/T OVHD MOVG E FQT
                                   LTGICCCCG

RS 0855 12 SCT E80 OVC          8   TRW-      2212 /985/T E MOVG E FQT LTG IC
                                   CC

SP 0938 M22 BKN 80 OVC          7          1610 /983/T MOVD E OCNL LTG
                                   CCG E - SE

RS 0955 22SCT E40BKN 80OVC      8          1806 /983/OCNL LTGCG E

SA 1055 25SCT 40BKN 200OVC      8          2204 /983
=====

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First Lightning Observed in Stated Range	TIME	TIME LAPSE (Min)
60 N. Mi	07:02	
50 N. Mi	07:14	12
40 N. Mi	07:21	7
30 N. Mi	07:47	26
20 N. Mi	07:56	9
10 N. Mi	08:07	11
		(8.1 N. Mi)
		3
5 N. Mi	08:10	(4.4 N. Mi)

Figure 19. Lightning Observations. The Upper Half is a Condensed Version of the Form 1-10 Surface Weather Observations Taken at Otis ANGB, MA. The Lower Half is a Representation of the Time that Lightning was First Observed within Selected Range Bins by the Lightning-Detection-System. The Time-Lapse between First Strikes is Noted.

occurred at a distance of 8.1 nmi. Two minutes later a strike occurred at a distance of 8.5 nmi. Within the next minute, another strike occurred at a distance of 4.4 nmi from Otis.

It is of great interest also to compare these observations with those taken by the observer at FMH. Given the restrictions to visibility, the observer is to be commended for his detailed observations. His first observation of distant lightning at 0755 was almost coincident with the system detection of a strike within the 20-mile range. His report of a thunderstorm at 0809 was two minutes later than the network observation of a strike located 8.1 nmi from FMH. Even though the agreement between the observer and the lightning system is striking, it is quite evident that there is a large disparity in detail between information derived from the two. In fact, so much information is produced by the LDS that algorithms are needed to condense the data base and to generate end products that are useful in operations.

4. LIGHTNING CLUSTER ANALYSIS

It quickly became apparent that the LLP RDP had numerous advantages as a real-time operational tool. At the same time it also became apparent that access to the lightning-strike data-base for research, evaluation and technique development was essential. In response to this need, Dynamics Research Corporation of Andover, MA developed software that would access the cassette tape archival system, read in data and store it in a Zenith Z-248 computer in a packed mode. Once the source data was on disk, an unpack program generated a chronological listing of lightning strikes with their respective latitudes and longitudes.

In order to meet the AWS requirements listed previously, algorithms and software must be developed to fill those areas that the commercial system does not cover. For example, the first two requirements list the need to compute the direction of movement of a lightning system and its time-of-arrival within various ranges of an installation. This will necessitate the development of an algorithm package similar to the composite hazards product generated for the NEXRAD.¹² In addition to showing past, present, and future positions of showers and thunderstorms, that product also displays growth trends, hail identification, and mesocyclone detection.

In an attempt to determine some of the essentials of a lightning products package, the lightning strike locations for the 11 August case were subjected to a more detailed study. Data were unpacked and programs were then written that could be activated by the specification of latitude and longitude. To focus on a particular lightning cluster, a search window of an optional size and location could be selected. Figure 20 shows an example of an x-y plot (160 × 240 nm window) of the lightning strike locations during the one-hour period shown in Figure 7. It is immediately obvious from the detail in this map that there are at least two clusters of strikes. A more sophisticated cluster identification algorithm would separate these systems and track them separately. For the purposes of this report, however, we continued to use the larger window-size and to accept some of its obvious shortcomings. A mean position of the composite cluster was determined (40.35 N; 75.58 W); the number of strikes

12. Forsyth, D.E., Istok, M.J., O'Bannon, T.D., and Glover, K.M. (1985) *The Boston Area NEXRAD Demonstration (BAND)*, AFGL-TR-85-0098 AD A164426.

LIGHTNING STRIKE LOCATIONS

0100-0159 GMT, 11 AUG 86 - 1288 STRIKES

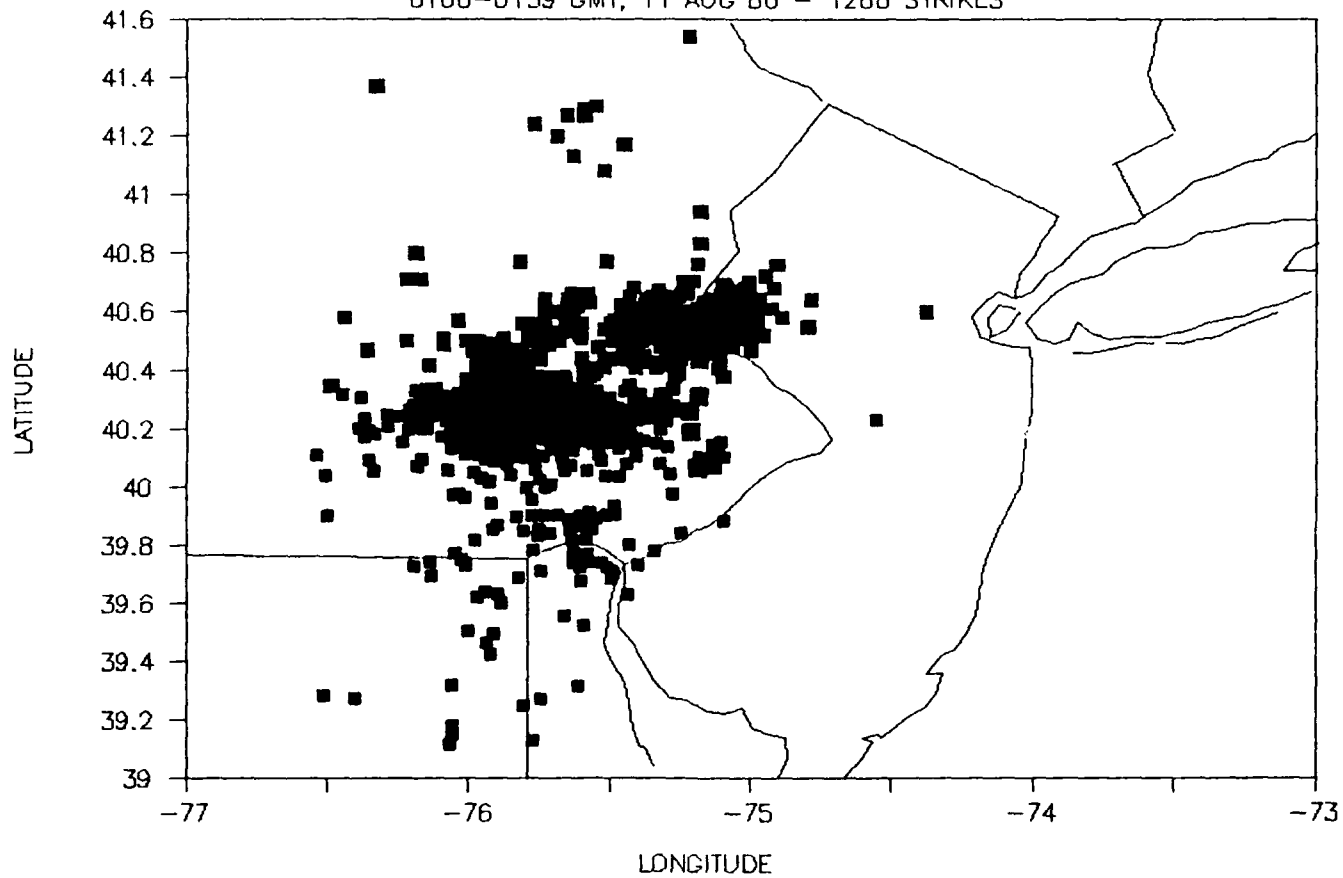


Figure 20. Lightning Strike Location Chart for the Period 01:00 to 02:00 UTC, 11 August 1986. Plot Obtained from Software Developed to Provide Operational Aids.

summed (1288); and the bearing and distance to Otis ANGB calculated (76 degrees/239 nmi). Since this was the first cluster examined, no velocity was obtained.

Figure 21 shows the hourly count of lightning strikes for the 9 hr period coinciding with Figures 7 to 15. The decreasing trend of lightning strikes with time is quite apparent, and would suggest dissipation of the storm within a few hours. A minimum (615 strikes) occurred between 0700 and 0800 (Figure 13) when the cluster located over eastern Long Island began to rapidly dissipate. During the next hour, however, activity increased to over 800 strikes/hour.

In Figure 22 the hourly positions of the lightning strike clusters are plotted with the location of Otis ANGB (FMH) shown. As in the previous figure, the 0130 location represents the mean position of the cluster of strikes that occurred between 0100 and 0159 UTC. The unsophisticated algorithm did not give a truly representative description of cluster locations and motions. Because of the large size of the sample-window, multiple clusters were averaged together, for example, Figure 20, and erratic displacements occurred. In addition, the computed 0730 location was shifted to the north by the dissipation of the southern cluster over Long Island. Simple extrapolation from the 0530 position and from the later positions bracket the actual arrival time within plus or minus 30-min. To detect the change of direction of the system in the last few hours of its lifetime however, would require that an alert feature be included in the program.

A summary of the experimental lightning display package is shown in Figure 23. Columns define the type of information depicted below for the lightning cluster calculations. A point should be made that the lightning count totals on this figure may differ from other maps of the same time period because different windows were used; for example, the total number of strikes in Figure 23 for the period is 1288 while the larger-area map, Figure 7 for the same time period shows a lightning count of 1559. An inspection of column 3 and column 4, the bearing to Otis and the velocity respectively shows a strong agreement. This agreement could be used as a trigger to set up an alert for FMH base operations. Techniques or algorithms that will consider cluster diameters and estimates of arrival times of the leading edge of clusters are, of course, topics of critical concern for further investigation.

5. LIGHTNING STRIKE ANALYSIS

Consideration of the wide fluctuations in time of the occurrence of lightning strikes in the range bins surrounding FMH, Figure 19, led to a decision to analyze in more detail the variations in space and time between consecutive events in a one-hour cluster, or swath, of lightning strikes. Figure 24 shows the one-hour plot of strikes during the period that the storm was almost centered over FMH. A circle with a radius of 40 nmi would enclose the main body of the strikes that occurred during the hour.

The time-lapse between consecutive pairs of strikes was determined and is illustrated in Figure 25. For the 893 pairs examined, the average time-lapse was 4 sec with a standard deviation of 3.8-sec. The maximum time lapse between two strikes was 25-sec and the minimum was 0. Activity during the hour reflects the continued steady state condition of the storm. No individual minute exhibited wide excursions in numbers of strikes.

HOURLY LIGHTNING OCCURRENCES

11 AUGUST 1986

N = 9693

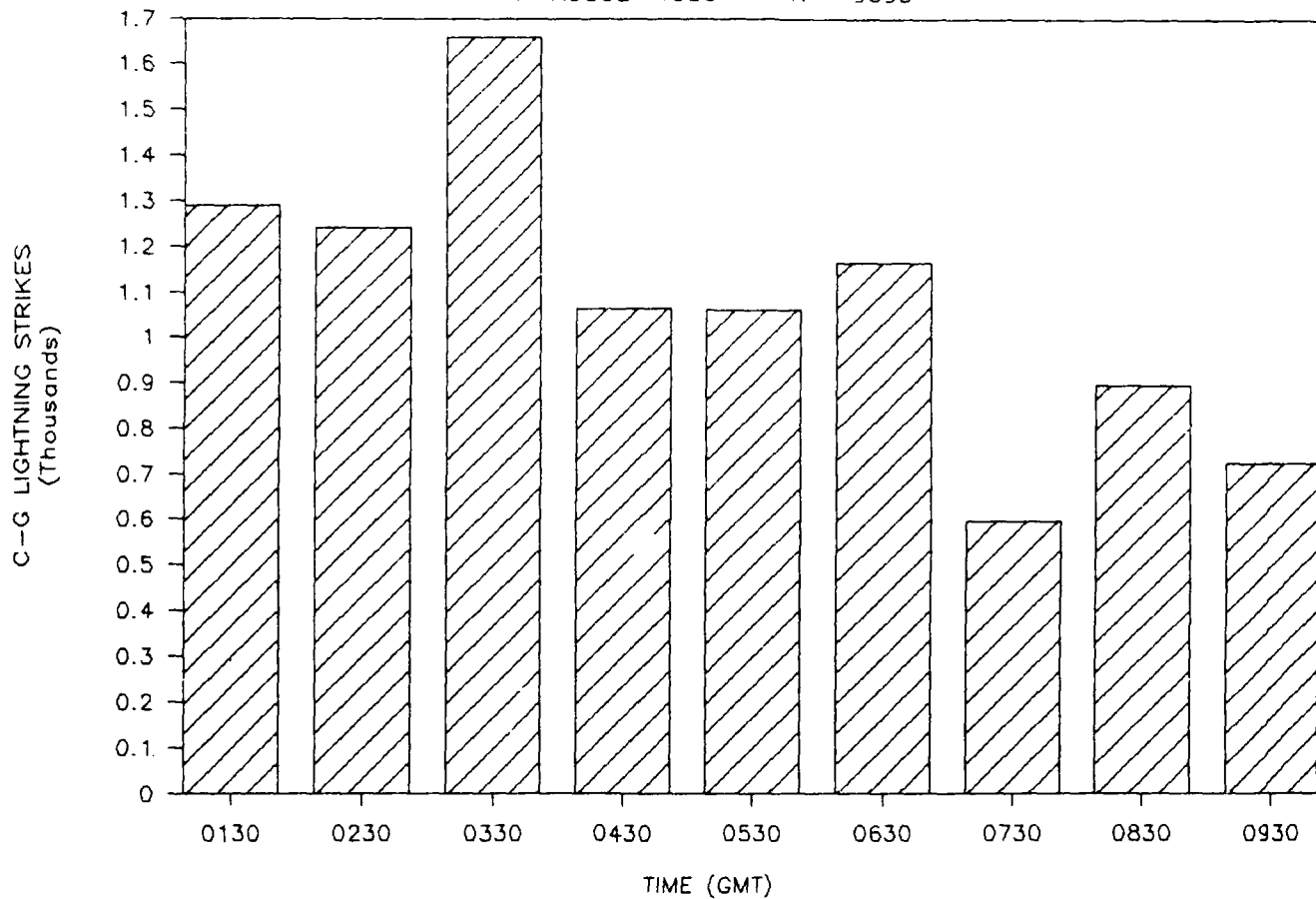


Figure 21. Hourly Lightning Strike Occurrences for the Period 01:00 to 10:00 UTC, 11 August 1986. Plot Obtained from Software Developed to Provide Operational Aids.

HOURLY LIGHTNING CLUSTER LOCATIONS

11 August 1986

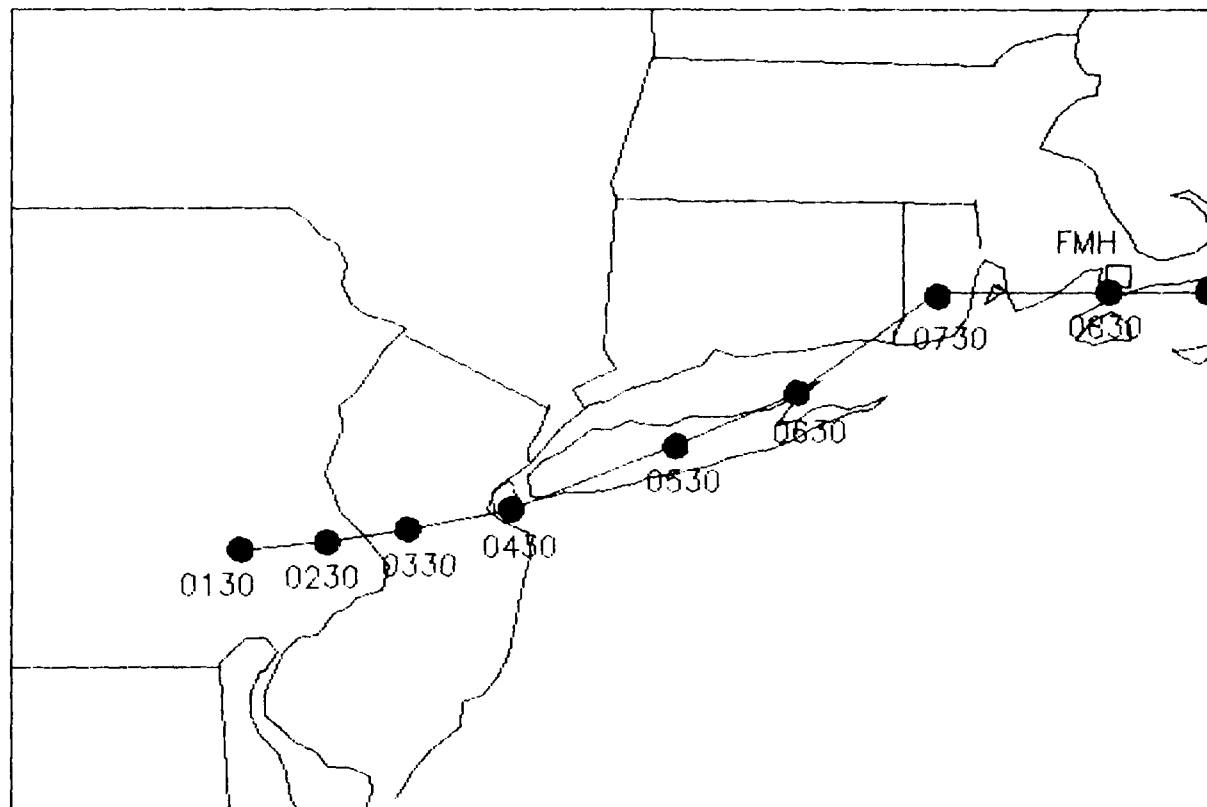
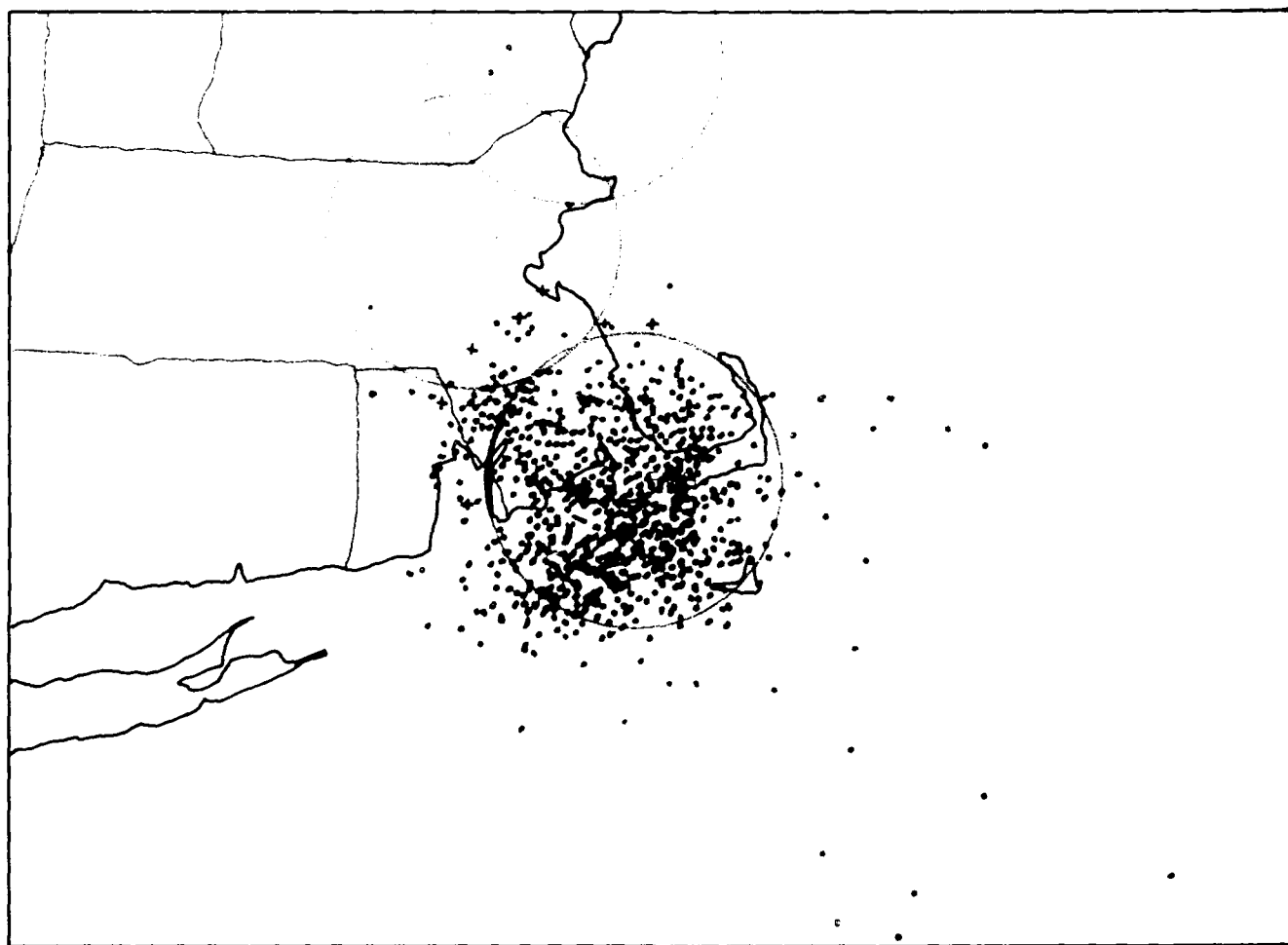


Figure 22. Plot of the Mean Positions of the One-Hour Clusters of Lightning Strikes for the Period 01:00 to 10:00 UTC, 11 August 1986. Plot Obtained from Software Developed to Provide Operational Aids.

TIME	CLUSTER LOCATION	DIR/DIS TO OTIS AFB, MA (FMH)	VELOCITY L1 TO L2	LIGHTNING STRIKES
0100 - 0159	LAT 40.35 LON 75.58	DIR 76 DIS 239 N.M.	80/17 Kts	1288
0200 - 0259	40.39 75.16	75 221		1240
0300 - 0359	40.42 74.77	74 204	85/18	1660
0400 - 0459	40.57 74.10	74 173	74/32	1064
0500 - 0559	40.84 73.11	73 126	70/48	1061
0600 - 0659	41.06 72.45	74 94	66/33	1165
0700 - 0759	41.54 71.60	85 81	53/48	596
0800 - 0859	41.55 70.64	16 21	89/42	894
0900 - 0959	41.55 70.00	292 33	90/29	725

Figure 23. Summary of the Software Developed to Provide Operational Aids. Time Intervals are Indicated in the First Column. Mean Positions of the One-Hour Clusters of Lightning Strikes are Given in the Second. Bearings and Distances from the Mean Position of the Cluster to a Point of Interest, in this Case Otis ANGB, MA, are Shown in the Third Column. The Velocity Derived from Cluster Locations is Shown in the Fourth Column. The Summation of Lightning Strikes for the Period Selected, in This Case One-Hour, are Given in the Fifth Column. The Period is from 01:00 to 10:00 UTC, 11 August 1986.



MAP 44 WIDTH = 260 NM 08:00:10 11-AUG-86 TO 08:59:58 11-AUG-86 FLASH TOTAL = 897
 ● / TIME KEY + > +

Figure 24. LLP Lightning Strike Location Chart for the Period 08:00 to 09:00 UTC, 11 August 1986. This Chart is a Zoom Version of Figure 14.

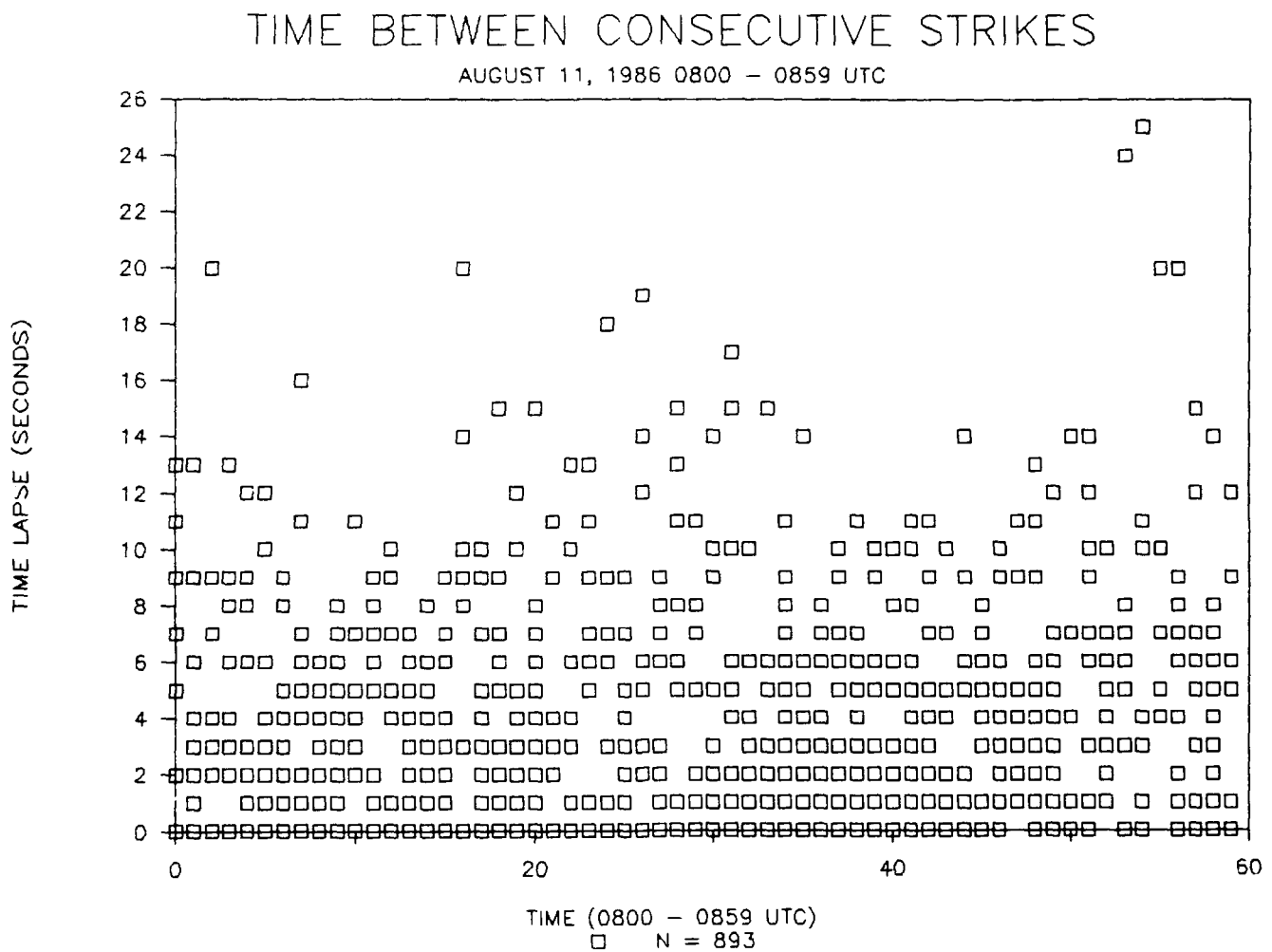


Figure 25. Plot of the Time-Lapse (sec) between Consecutive Strikes for the One-Hour Period, 08:00 to 09:00 UTC, 11 August 1986

The distance between consecutive strikes was calculated and plotted in Figure 26. The average distance between consecutive strikes during this hour was 23.9 nmi with a standard deviation of 15.7 nmi. The maximum distance between strikes was 124.7 nmi and the minimum distance was 1.3 nmi.

The large distances between consecutive strikes indicated that the window-size was too large and the time plot was too long. It was likely that activity occurring in smaller clusters was being masked by the composite plot. Also, strikes could be occurring alternately in separate clusters of activity and the distances then would be incorrect. The hour's activity was divided into 10-min segments and the plots are shown in Figures 27 through 32. The open square marks the location of FMH. As suspected, at least two distinct smaller-scale clusters are revealed in the first 10-min plot. In Figure 28 the two clusters are still evident but in Figure 29, 10-min later, the two clusters have almost merged. In Figure 30, a small cluster has separated in the north with a larger cluster in the south. In Figure 31 a complex group suggests smaller clusters to the south and to the north. During the last 10-min period, Figure 32, two small clusters are again evident with scattered strikes as outliers. In general, examination of the 10-min plots did not greatly simplify the interpretation of the structure of cellular activity in a complex convective system.

To determine the distances between consecutive strikes within the smaller-scale centers of activity, the northern cluster in Figure 27 was reanalyzed only for the strikes within its boundaries. This eliminated the possibility of calculating distances between consecutive strikes that occurred in different clusters. As a result, the average distance between consecutive strikes in the north cluster was recalculated to be 15.5 nmi with a standard deviation of 7.2 nmi. The maximum distance was 40 nmi and the minimum distance, 1.8 nmi.

Consideration of the distance between strikes in a thunderstorm is, of course, a complex problem. One must consider the number and size of active cells, the lifetime of individual cells, the translation velocity of the cells, and the accuracy of the strike location. A good illustration of some of these points was made in a study of thunderstorm activity over northern Kyushu in Japan.¹³ The paper showed visually determined lightning strike locations and observed times of occurrence over a period of one hour. The strike cluster patterns are very similar to those observed in this report. From this information a distance-time diagram was plotted and the mean speed of the lightning activity was obtained. On plotting the strike locations relative to the moving system, the areal distribution of the strikes was resolved and concentrated into three small cellular storms.

For air base operations, however, the approach of an electrical storm requires: (1) the observation of the event by the detection system, (2) an estimate of the time of occurrence of lightning activity within certain distances of the base, and (3) the triggering of an alarm when it actually occurs. In order to examine the storm in this framework, the azimuths and distances of strike locations with respect to FMH were calculated for the same hour considered in the previous discussion. Figure 33 shows a time-distance chart of these strikes. Each minute of the hour has a plot of all lightning strikes that occurred within 20 nmi of FMH. The closest strike to Otis in each minute has been connected by a straight line. The strikes reported at 0807, 0809 and 0810 were discussed in Section 3.3. The difficulty

13. Fujita, T. (1950) Microanalytical study of thunderstorm, *Geophysical Magazine of Japan* **22**: 78-88.

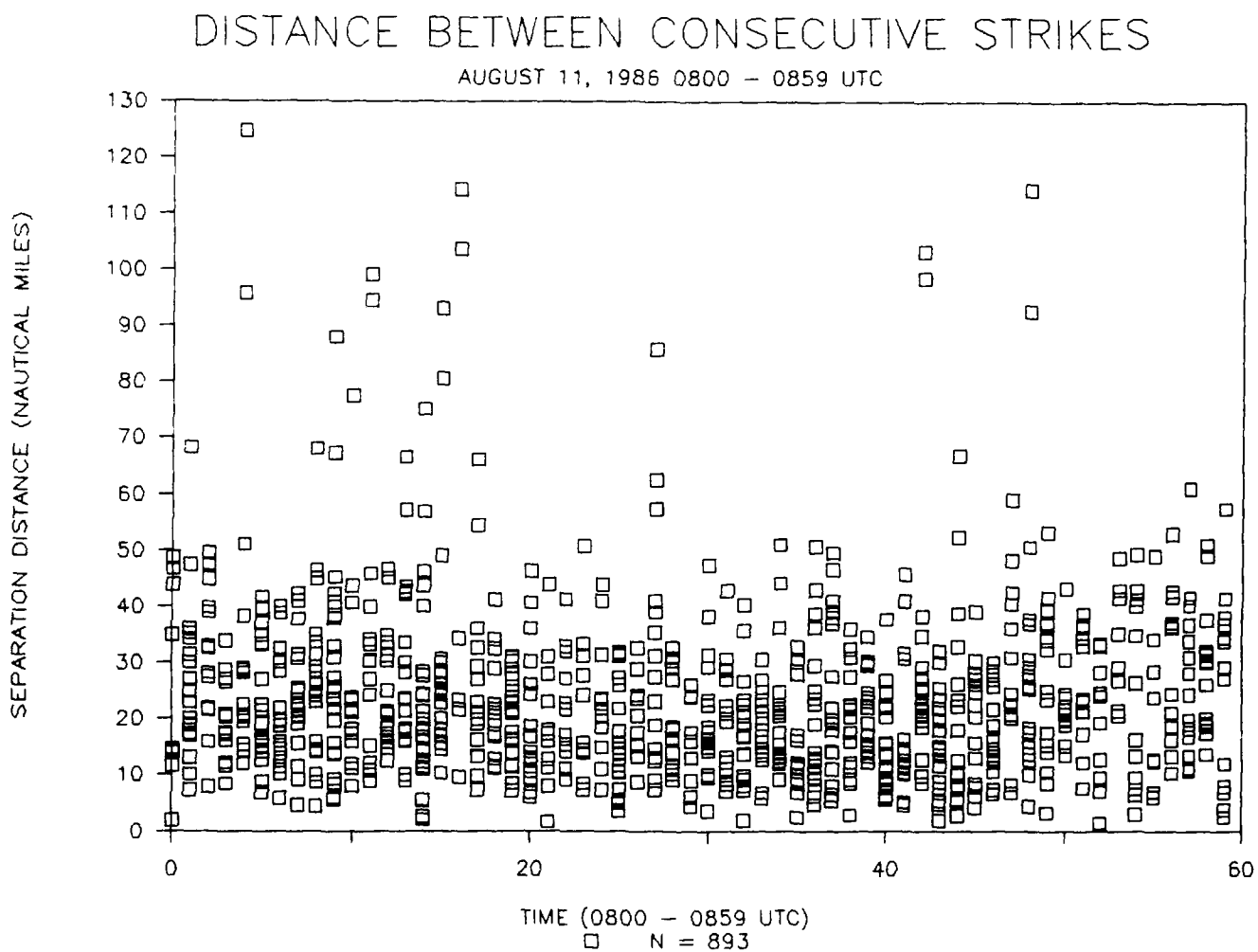
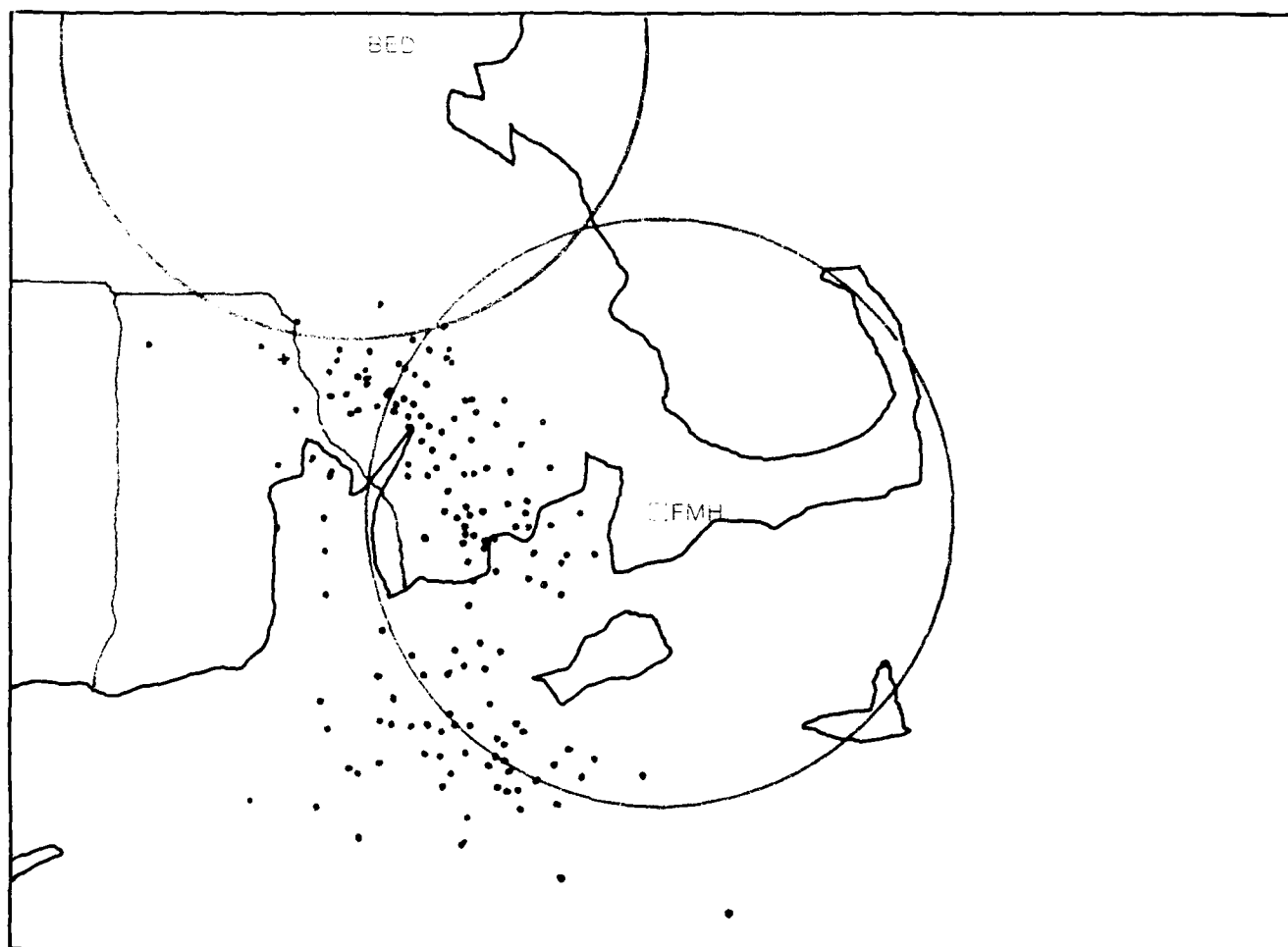
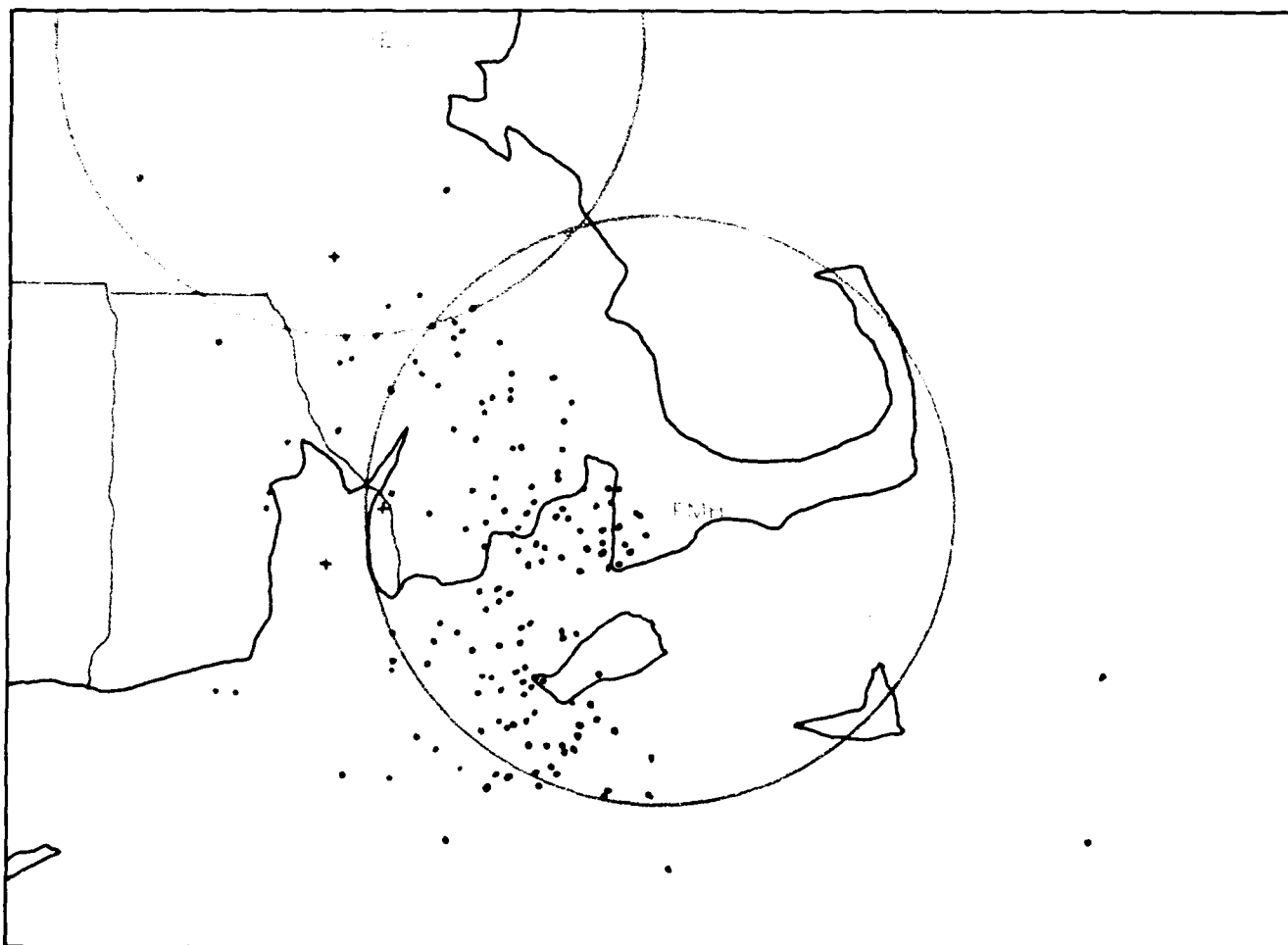


Figure 26. Plot of the Distance (nmi) between Consecutive Strikes for the One-Hour Period, 08:00 to 09:00 UTC, 11 August 1986.



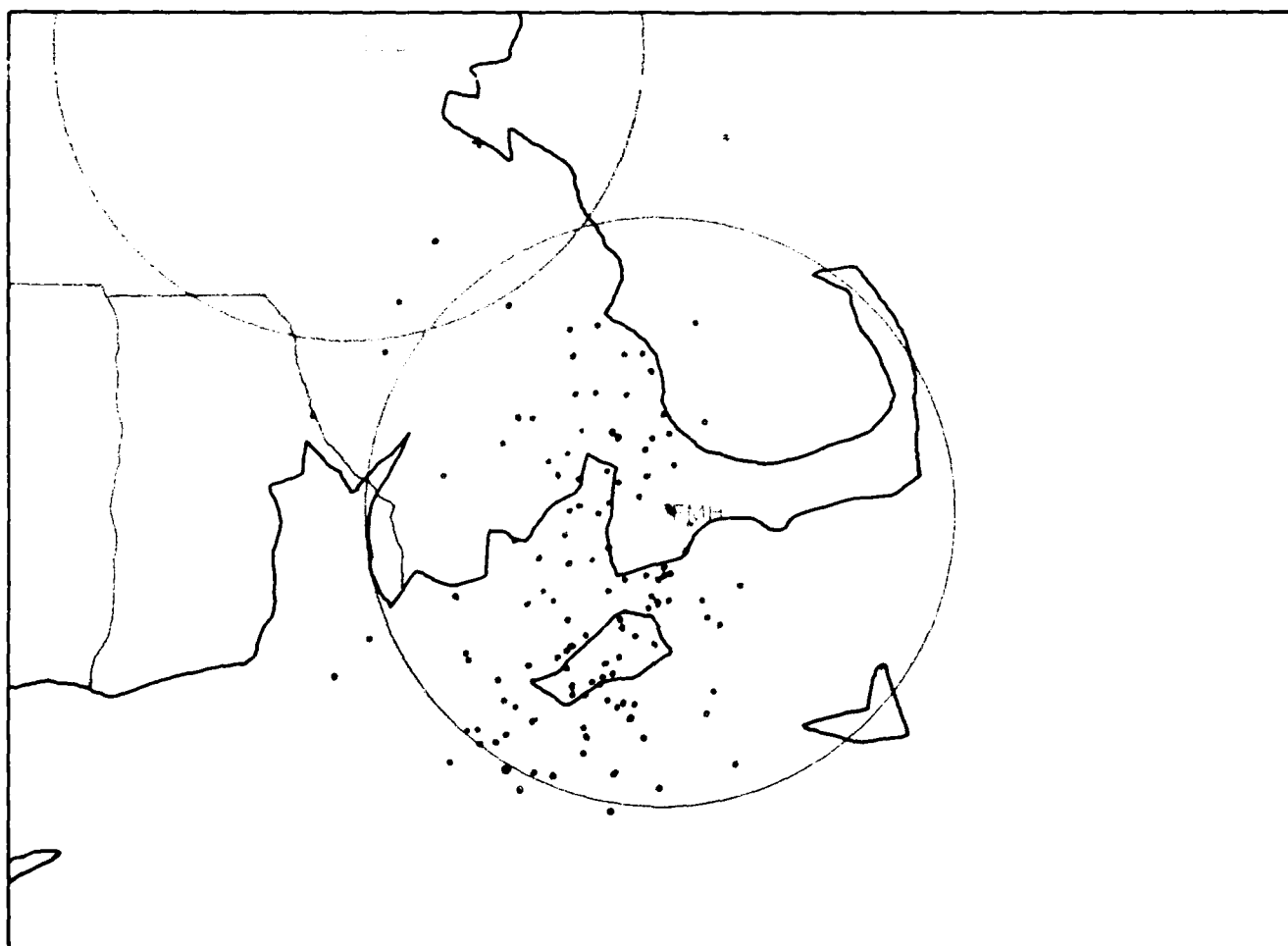
MAP 75 WIDTH = 133 NM 08:00:10 11-AUG-86 TO 08:09:56 11-AUG-86 FLASH TOTAL = 159
 • < - TIME KEY + > +

Figure 27. LLP Lightning Strike Location Chart for the Period 08:00 to 08:10 UTC, 11 August 1986.



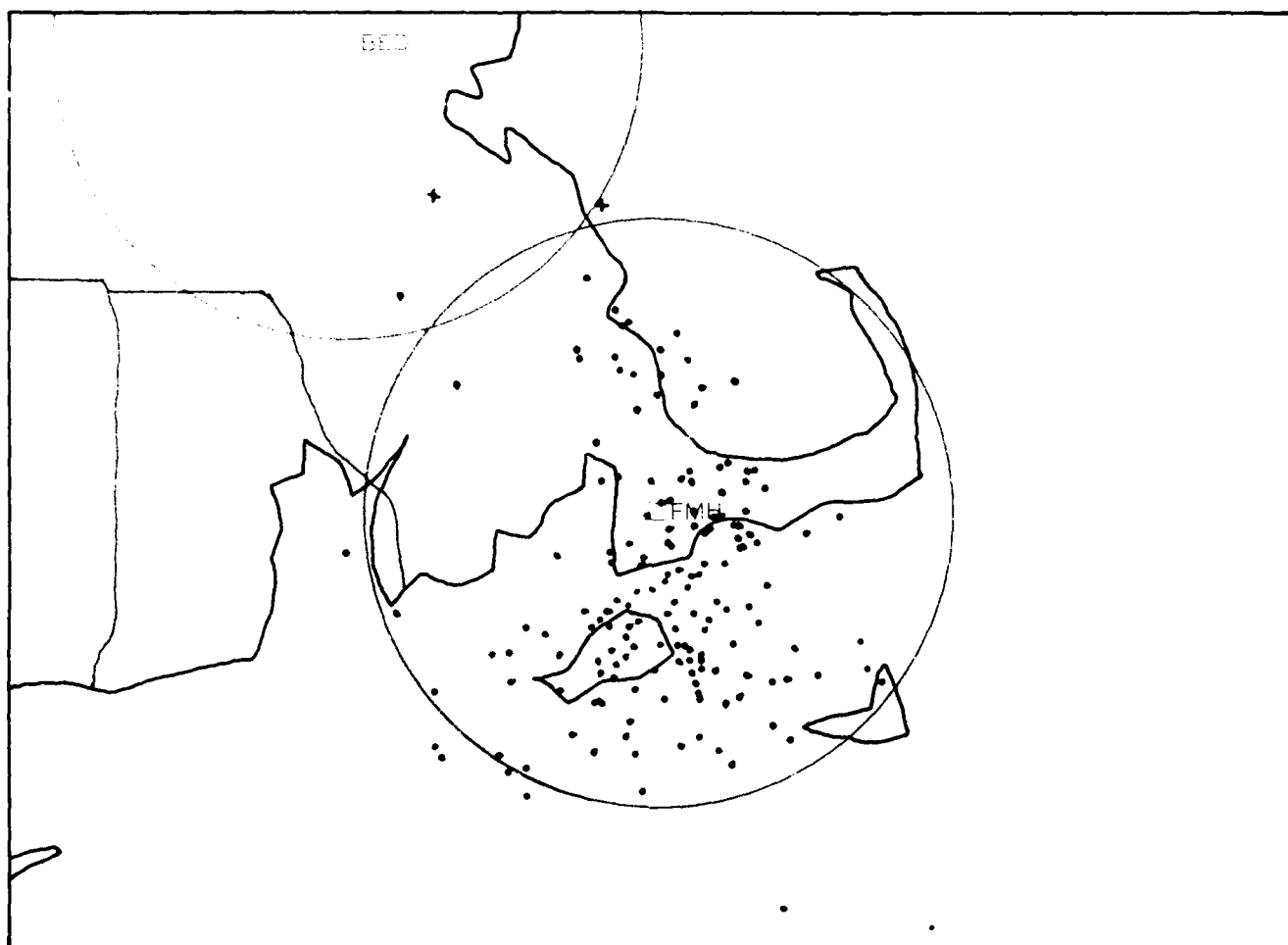
MAP 75 WIDTH= 133 NM 08:10:00 11-AUG-86 TO 08:19:59 11-AUG-86 FLASH TOTAL= 158
 ● < - TIME KEY + > +

Figure 28. LLP Lightning Strike Location Chart for the Period 08:10 to 08:20 UTC, 11 August 1986.



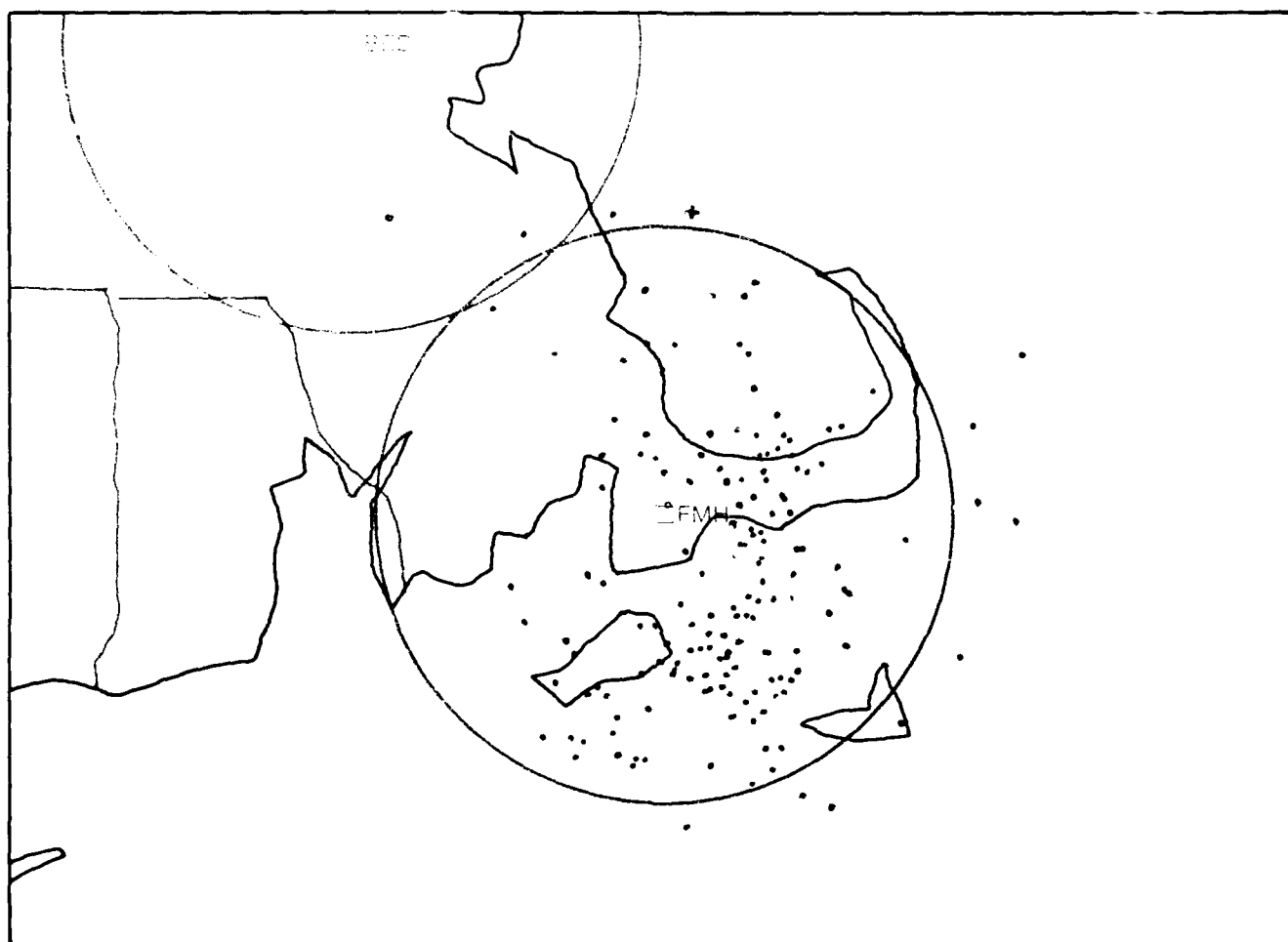
MAP 75 WIDTH= 133 NM 08:20:00 11-AUG-86 TO 08:29:52 11-AUG-86 FLASH TOTAL= 125
 • < - TIME KEY + > +

Figure 29. LLP Lightning Strike Location Chart for the Period 08:20 to 08:30 UTC, 11 August 1986.



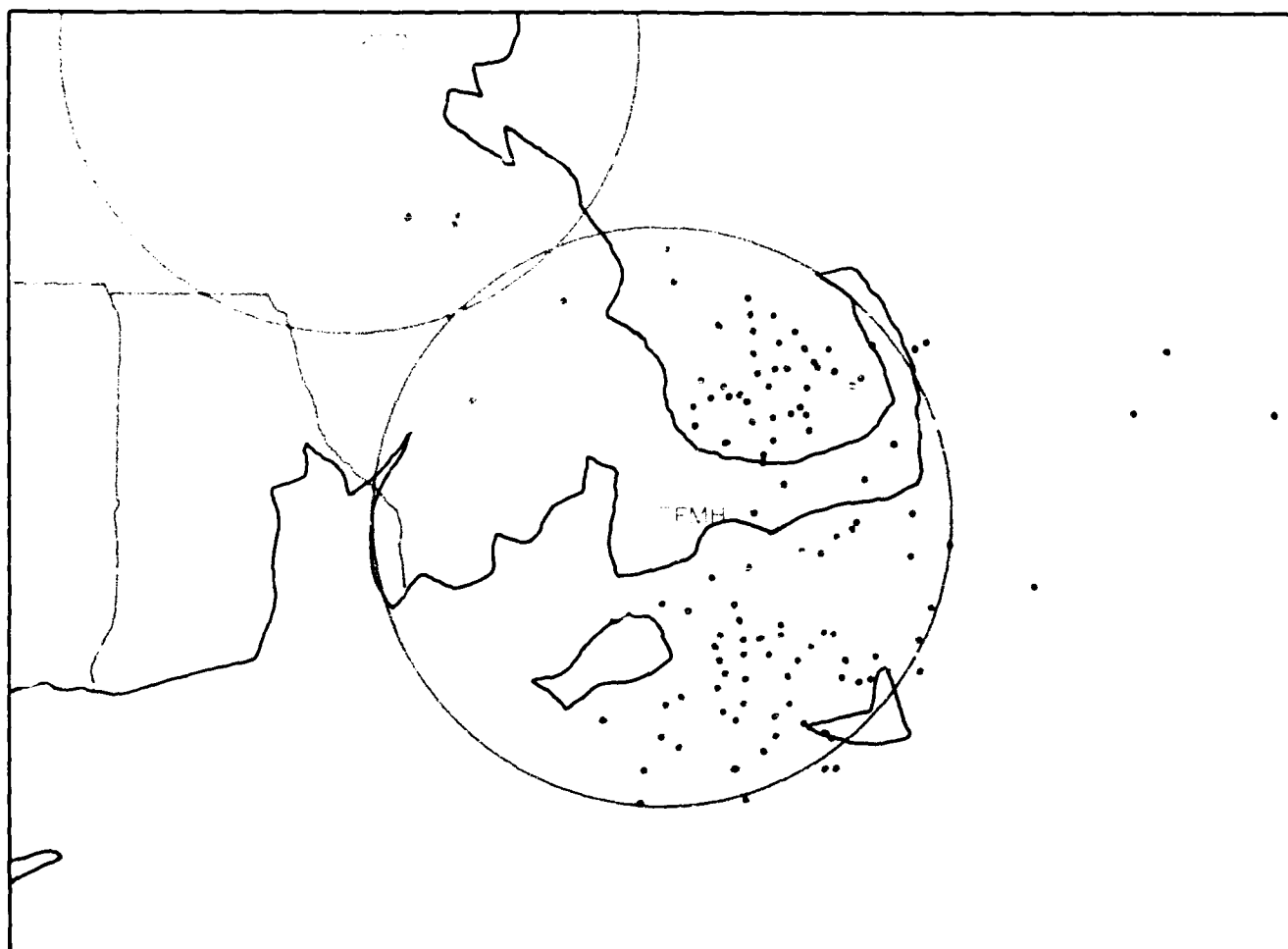
MAP 75 WIDTH= 133 NM 08:30:00 11-AUG-86 TO 08:39:52 11-AUG-86 FLASH TOTAL= 164
 ● < - TIME KEY + > +

Figure 30. LLP Lightning Strike Location Chart for the Period 08:30 to 08:40 UTC, 11 August 1986.



MAP 75 WIDTH= 133 NM 08:40:02 11-AUG-86 TO 08:49:53 11-AUG-86 FLASH TOTAL= 160
 ● < - TIME KEY + > +

Figure 31. LLP Lightning Strike Location Chart for the Period 08:40 to 08:50 UTC, 11 August 1986.



MAP 75 WIDTH = 133 NM 08:50:00 11-AUG-86 TO 08:59:58 11-AUG-86 FLASH TOTAL = 118
 ● < - TIME KEY + > +

Figure 32. LLP Lightning Strike Location Chart for the Period 08:50 to 09:00 UTC, 11 August 1986.

LIGHTNING STRIKE DISTANCES FROM FMH

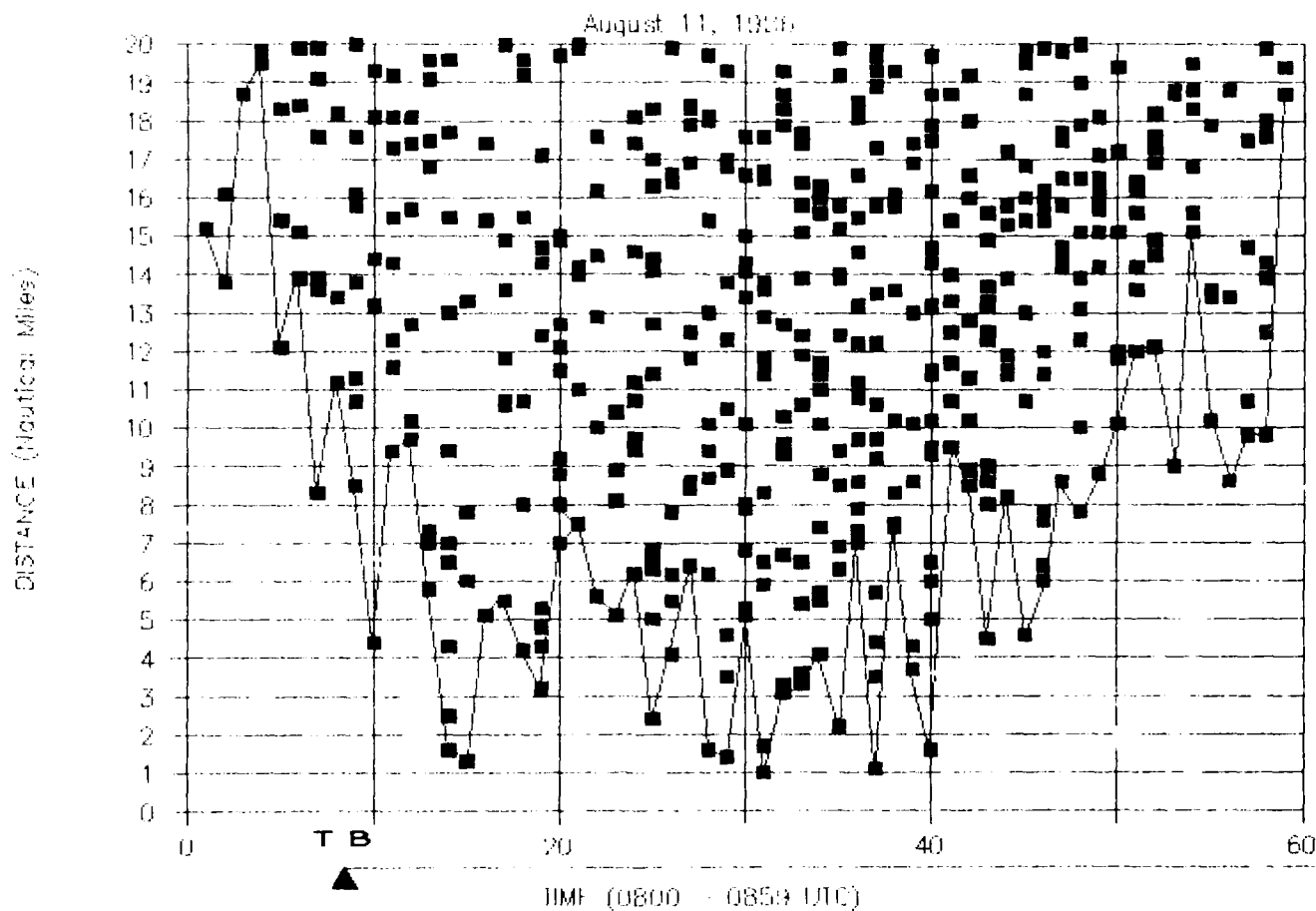


Figure 33. Plot of the Distance (nmi) of Consecutive Strikes from Otis ANGB (FMH) for the One-Hour Time Period, 08:00 to 09:00 UTC, 11 August 1986. Straight Line Segments Join the Closest Strike to FMH for Each Minute of the Hour. The FMH Observed Thunderstorm Period is Marked Below the Plot.

of estimating a precise time when a strike will occur within a given range of an air base, for example, five nautical miles, is graphically displayed. On the other hand, referring to the maps seen in Section 3.2, one could have predicted with great confidence that FMH would be subjected to a severe electrical storm within a well-defined time period.

6. SUMMARY AND PLANS

This report represents the first in a series of reports to describe the direction and the progress of the AFGL AOS effort in the automation of lightning observations. For the purpose of clarification, the several lightning investigations being conducted at AFGL are outlined:

(1) LLP Remote Display Processor (RDP) and the SUNY-Albany Lightning Detection Network. Demonstrate, with a case study, the features of a commercially available hardware display coupled with a DF-Triangulation Network and its potential as an observing and forecasting instrument. This is the subject of the present report.

(2) LLP Remote Display Processor (RDP) and the SUNY-Albany Lightning Detection Network. Study the performance of the DF network (NE half of the SUNY-LDN) in comparison with 25 Air Force weather stations located in the northeast United States. The months selected for analysis were July and August 1986. Determinations were made of (a) Detection Efficiency, (b) False-Alarm Rate, (c) Missed Threat Rate, and (d) Critical Success Index. This report is currently in draft form.

(3) SUNY-Albany IBM Display Processor (with THUNDER software) and the SUNY-Albany Lightning Detection Network. There are two goals in this study: (a) Demonstrate the potential of the SUNY software THUNDER coupled with the IBM computer system and the DF network as an observing and forecasting instrument, and (b) Continue the performance study of the DF network (entire SUNY-Albany LDN) by comparing its observations with 42 Air Force weather stations located along the east coast of the United States. The months selected for analysis were July and August 1987. This analysis is about one-half completed.

6.1 Results of the Study of LLP RDP and SUNY-Albany LDN

The RDP has the capability to display the location, motion and evolution of observed lightning clusters in both space and time. The RDP is a pre-programmed microcomputer that generates a high-resolution color video display of the lightning locations superimposed on user-defined geographical detail. The data are plotted in near real-time (5 to 20 sec lag) and can be archived in a permanent device. They are also stored in random-access memory, which in the AFGL system allowed for the retention of the latest 25,000 strike locations. These data can be played back and displayed on any of a user-defined set of 100 maps. The processor can be operated in any of six operating modes. Two of the modes are used in real-time applications, the remainder are used in displaying the stored data.

With reference to the Air Force lightning requirements listed in Section 1.1, results of this study show that the LLP RDP coupled with the SUNY-Albany LDN, displayed cloud-to-ground lightning strikes well beyond the 200 nmi boundary. The detection efficiency of the system was not determined in this study; however, the storm of 11 August suggests that a case could be made that something less

than 100 percent detection efficiency should be satisfactory. A storm that is observed to have 1200 strikes/hour and has existed as a well-defined strike-cluster for about 10 hours is a storm to cause alarm. The fact that the storm may have generated more than 1200 strikes/hour becomes a problem of developing scaling factors of severity versus observed strike count. Further research using new data bases generated by lightning detection systems are expanding the knowledge of lightning and its inter-relationships with other weather variables (for example, radar, etc.).^{14,15,16,17}

The LLP RDP has six-colors that can be assigned to time intervals for video display and color hard copy. It does not have the ability to compute the direction of movement and time of arrival of a lightning-producing system within preset ranges. It was demonstrated, however, that this capability is achievable with further software development. The RDP has an audible warning device that is triggered by a strike within a map region. Therefore, if a map, for example, 120 nmi $\times$ 120 nmi is selected with an air base centrally located, a 60 nmi audible alarm feature will exist.

The position accuracy of the system was not determined in this study. This question and the analysis of other lightning systems are the subjects of ongoing research at other federal agencies. Their studies are being monitored and their results will be incorporated into future recommendations.

The Air Force lightning observation requirements for flying safety, Section 1.1b, of all types of lightning are not met by any system currently in existence. The DF and the TOA systems observe cloud-to-ground strikes only. The Air Force requirement of a data base for research applications is partially met in the ability of the RDP to archive the time, latitude and longitude of each cloud-to-ground strike recorded.

It should be noted that shortly after the LLP RDP was delivered to AFGL and connected to the SUNY-Albany Lightning Detection Network, a new model RDP was announced by LLP, Inc. The new system, named ISIS, has many new features that are distinct improvements over the RDP. The ISIS features a keyboard for commands rather than the RDP dials. It has a zoom command that eliminates the need to select pre-programmed maps. The limit of 100 pre-set maps is, of course, eliminated. Another feature is the ability to receive radar maps and overlay them on the lightning maps.

The use of the RDP and the lightning detection system as an observing and forecasting tool was revealed graphically in the hour-by-hour progress and evolution of an electrical storm as it formed in Pennsylvania, moved across Long Island and advanced on Cape Cod. The persistence of this storm gave great confidence in estimating its time of arrival in the New England area. Some examples of

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14. Holle, R.L. and Maier, M.W. (1982) Radar Echo Height Related to Cloud-to-Ground Lightning in South Florida, Proceedings of the 12th Conference of Severe Local Storms, Amer. Meteorol. Soc., San Antonio, TX.
 15. Orville, Sr., R.E., Pyle, R.B., Henderson, R.W., Orville, Jr., R.E., and Weisman, R.A. (1985) Characteristics of cloud-to-ground lightning flashes along the east coast of the United States, 10th International Aerospace and Ground Conference on Lightning and Static Electricity, Paris.
 16. Lopez, R.E. and Holle, R. (1986) Diurnal and spatial variability of lightning activity in northeastern Colorado and central Florida during the summer, *Mon. Wea. Rev.* **114**:1288-1312.
 17. Reap, R.M. (1986) Evaluation of cloud-to-ground lightning data from the western United States for the 1983-1984 summer seasons, *J. Climate and Appl. Meteor.* **25**:785-799.

software products that were developed showed a method of tracking individual clusters and generating mean positions, velocities and strike counts.

To illustrate the use of the system in an observational mode, comparisons were made between system reports of lightning within prescribed range bins and the observations made by the weather observer at FMH. A further analysis was made to show, on a 1-min time scale, the wide variability in distance of lightning strikes as a storm approaches an air base.

6.2 Recommendations

During the last few years, a Working Group of the Office of the Federal Coordinator for Meteorology (OFCM) has met to examine the feasibility of a National Lightning Warning Network and to make recommendations for its installation. In 1987 a contract was issued to SUNY-Albany to set up a three-year demonstration of an experimental National Warning Network. This would be achieved by establishing data communication links from the computer center at the Boise office of the Bureau of Land Management (the Rocky Mountain BLM Lightning Detection Network) and the computer center at the National Severe Storms Laboratory (the Great Plains Lightning Detection Network) to the SUNY-Albany LDN computer. The combination of the West Coast and the Great Plains networks with the SUNY-Albany East Coast network would effectively give an east-to-west coast coverage with the LLP-type DF sensors. As a part of the contract, any Federal agency could receive the experimental data for test purposes by acquiring or allocating a compatible personal-type computer and paying the communication cost to the facility. This experimental network is now in operation, (Figure 34), and it is understood that SUNY-Albany is planning to install DFs in the midwestern region to complete the nation-wide coverage. It is highly recommended that the Air Weather Service install a compatible computer system at the Global Weather Central, Offutt AFB, NE so that the experimental network can be monitored and the potential of such a system can be experienced first-hand. The system that would be acquired is the same system that will be analyzed and presented in 3(a) of the Summary, Section 6. Based on the experience gained at AFGL since the system was installed, it is very apparent that this lightning detection system is an extremely valuable tool for the meteorologist. The fact that it does not yet meet all the requirements of an automated observation sensor should not preclude the consideration of its inclusion in the Air Force inventory of weather sensors. Its value as an operational forecasting-briefing-planning system, to be used in the weather station or weather central, is independent of its value as a component of an automated weather observation system. Further research and development will eliminate many of the shortfalls in the current system. The coupling of a satellite (cloud boundaries) system and a radar (precipitation boundaries) system with a lightning detection system will present the meteorologist with an excellent set of observations to pinpoint, on an even smaller scale, the cores of electrical activity in storm systems and to issue warnings of impending threats to Air Force assets and operations.

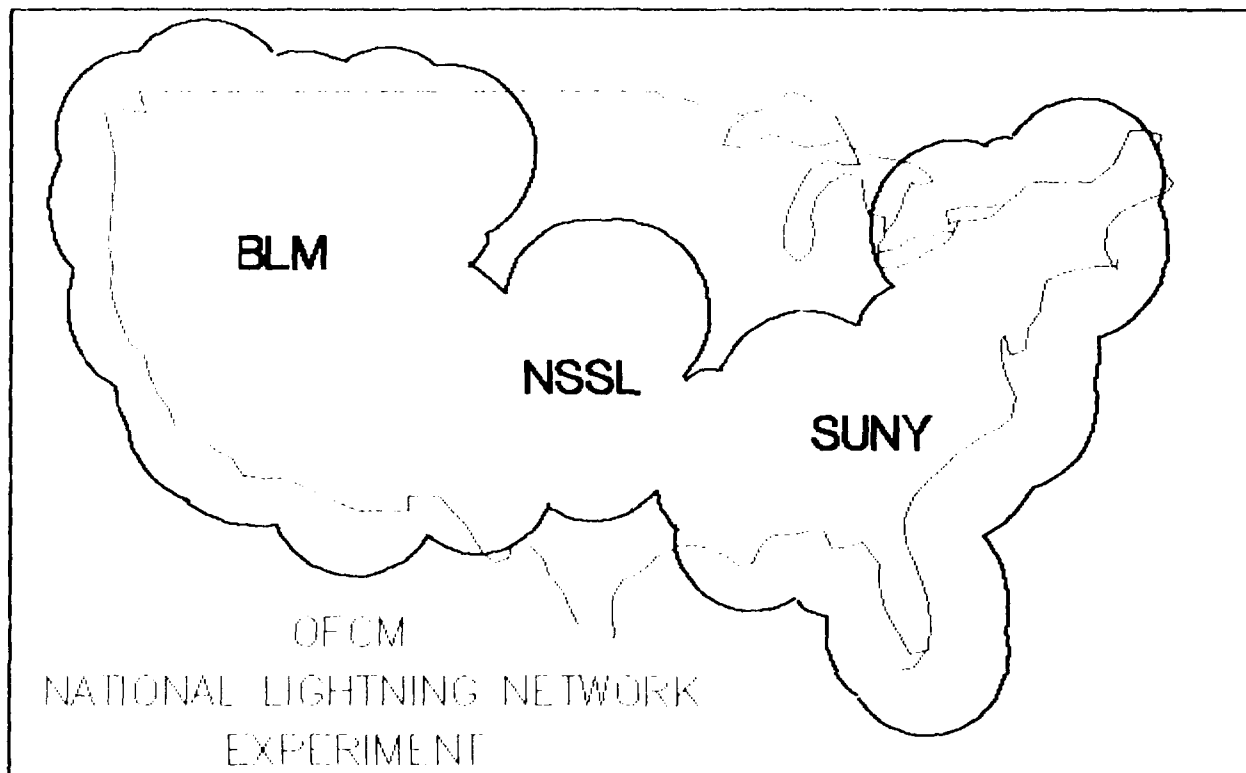


Figure 34. The Office of the Federal Coordinator for Meteorology (OFCM) Experimental National Lightning Network. A Zone of Coverage Around Each of the Three Participating Networks is Shown.

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