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THE SPATIAL VARIATIONS OF LIGHTNING DURING SMALL FLORIDA THUNDERSTORMS

Timothy D. Oram and E. Philip Krider
Institute of Atmospheric Physics
University of Arizona
Tucson, Arizona 85721

ABSTRACT

Networks of field mills (FMs) and lightning direction finders (LDFs) have been used to locate lightning over the NASA Kennedy Space Center (KSC) on three storm days. Over 90 percent of all cloud-to-ground (CG) flashes that were detected by the LDFs in the study area were also detected by the FM network. 27 percent of the FM lightning events were correlated with CG flashes detected by the LDFs. About 17 percent of the FM CG events could be fitted to either a monopole or a dipole charge model. These projected FM charge locations are compared to LDF locations, i.e. the ground strike points. We find that 95% of the LDF points are within 12 km of the FM charge, 75% are within 8 km, and 50% are within 4 km. For a storm on July 22, 1988, there was a systematic 5.6 km shift between the FM charge centers and the LDF strike points that might have been caused by the meteorological structure of the storm.

INTRODUCTION

The forecasting and detection of atmospheric electrical hazards at the USAF Eastern Space and Missile Center (ESMC) and the NASA Kennedy Space Center (KSC) are critical for safe launch and ground operations. Following the Apollo 12 incident in which the Saturn V rocket was struck twice by lightning, the USAF and NASA installed a network of field mills to measure cloud electric fields near the launch complexes. The field mill network can also be used to detect and locate lightning [1]. Also, a network of gated, wideband magnetic direction finders, manufactured by Lightning Location and Protection, Inc. (LLP), is used to locate CG lightning [2,3] in the ESMC-KSC area. These sensors respond to the magnetic fields produced by the return strokes in negative CG lightning, and they do not respond to cloud discharges. USAF and NASA launch criteria currently state that vehicles may not be launched if a 1 minute average of the absolute value of the cloud electric field exceeds 1000 Volts per meter within 5 nm (9.25 km) of the launch site within 15 minutes prior to launch. In addition, a launch cannot take place if lightning is detected within 10 nm (18.5 km) of the launch complex [4].

Several authors [5–8] have described methods of determining lightning charge locations using the field mill network. It is usually assumed that the spatial pattern of the abrupt field changes that are due to lightning can be described by either a monopole or dipole charge model. The monopole or point-charge model is thought to be the best description of CG lightning, while the dipole describes intra-cloud lightning [6]. In our analyses, we have tried both models on each lightning event, and we have systematically varied the parameters of these models until we have an optimum description of the measured field changes. We measure "the goodness of fit" using a standard chi-square function,

$$\chi^2 = \frac{1}{N_f} \sum \frac{(E_i - E_{mi})^2}{\sigma_i^2}$$

where N_f is the number of degrees of freedom (number of measurements minus the number of model parameters), E_i is the measured field change, E_{mi} is the modeled field change, and σ_i is the random error expected in the measurement at site i.

Several authors have tested the general accuracy of the FM locations by comparing them to visible lightning channels, television records or thunder measurements [5,9,10]. To the best of our knowledge, no one has yet compared the FM locations of CG lightning to the LDF locations. Obviously, a study such as this might have important consequences for the evaluation of launch constraints and the methods that are used to detect and locate lightning and to measure lightning distances.

In the following, we will describe the sources of our data, the analysis procedures, and our attempts to estimate the errors in the locations. The effectiveness of the two detection systems will be discussed, and then we will give preliminary results on the spatial variations of the FM charge centers and the LDF ground strike points.

DATA AND ANALYSIS PROCEDURES

GROUND STRIKE LOCATIONS: The LDF network computes the locations of the ground strike points from the intersection of magnetic direction vectors. The sensors are located at the Melbourne Regional Airport (DF #1), located about 70 km south of the rocket triggered lightning site (see Figure 1), the Orlando International Airport (DF #2), about 70 km west, and DF #3, about 2 km south of the rocket triggered lightning site. The measured angles are subject to both random and systematic or "site" errors. The systematic errors can be estimated and corrected using a procedure discussed by Hiscox et al. [11] and Lopez and Passi [12]. In order to estimate the true location, a site correction factor is applied to each LDF. The intersection of the corrected angles then gives the location of the ground strike point. When all three LDFs detect a flash, an "error triangle" may be formed from the intersections of three vectors.

In order to verify that we have derived the proper site correction factors, we have examined the locations of rocket-triggered flashes that were produced in the KSC Rocket Triggered Lightning Program. The dates, times, location, and position differences for these events are summarized in Table I. Note that for LDFs 1 and 2, the measured angles are all within the 1 degree random error that we expect in an LDF, that the East-West (X) components of the location errors are typically 0.5 km, and that the errors in the North-South (Y) components are less than 2.0 km. Rocket-triggered events almost always cause LDF 3 to over-range, so the location of these events are determined just by the intersections of LDFs 1 and 2. We expect that the rather large Y errors are caused by the large baseline distance from the RTL site to DF 2 (Orlando).

TABLE I: ROCKET TRIGGERED LIGHTNING EVENTS

		ANGLES			ERRORS (km)	
DATE	TIME	DF 1	DF 2	DF 3	ΔX	ΔY
IDEAL		352.2	64.4	355.2	0.	0.
7/25/88	21:18:52	351.6	65.7	NA	-0.4	-2.2
8/20/88	21:38:25	351.9	64.6	(344)	-0.2	-0.7
8/20/88	21:51:43	351.6	64.7	(0.4)	-0.5	-1.0
8/22/88	21:37:33	351.8	65.5	(233)	-0.2	-1.9
8/25/88	16:08:19	352.6	65.4	(356)	0.7	-1.3

ELECTRIC FIELD: The field mill sensors and sites have been described previously by Jacobson and Krider [5]. During 1988, the locations of the FM sites were as shown in Figure 1. (Note: The field mills are numbered from 1 to 34, but mills 3, 24 and 31 were not in service during 1988.) The electric field was digitized with 30 V/m resolution over a dynamic range that went from -15 kV/m to 15 kV/m. The field values were recorded at about 5 samples per second together with the hour, minute and second of the observation. For those events where only four samples were taken in a 1 second period, the value of the fourth measurement in the second was used for the fifth so as to "pad" the data.

The analysis procedure began by using an interactive program to identify the approximate time of each lightning discharge from simultaneous, abrupt changes in the electric field. An automatic slope projection algorithm was then used to determine the initial and final field values at each FM site and the change in the electric field was calculated. A Marquardt algorithm was then used to find the model parameters that minimized the chi-square function. The values of the model parameters at the minimum are assumed to be the optimum location and magnitude of the lightning charge or the dipole moment. Previous authors have required that there be a minimum field change value at a given number of FM sites before the flash was analyzed. Here, there was no analysis threshold except the practical limit of about 90 V/m.

The algorithm began with an initial guess for the X and Y parameters that were assumed to be the same as the X and Y location of the field mill with the largest electric field change. A search was then conducted on a 3 by 3 by 3 grid with dimensions 10 km by 10 km horizontal and 4 km vertical centered at an altitude of 8 km to improve the starting parameters. The starting charge was assumed to be 10 C for a monopole solution, and the starting vertical dipole moment was -50 C-km for a dipole solution. The Marquardt algorithm was run 27 times using the grid starting parameters for each model type, and then the solution with the lowest root mean square error was chosen as the best solution. For those FM lightning events that coincided with an LDF location, the Marquardt algorithm was re-run using the LDF location in place of the reference field mill starting location. This new ensemble of 27 solutions was then compared to the previous best and then the final best was selected. A solution was rejected if the chi-square value was significant at less than the 80 percent level or if the uncertainties in the X, Y or Z parameters were greater than 1 km.

In order to estimate the effect of random measurement errors on the model parameters, known charges were placed on a grid above the network and then the ideal field change was computed at each field mill site. A random error was then added to these field changes and the analysis algorithm run as described above. This procedure was repeated 100 times at each grid point, and then an average parameter error and standard deviation was calculated. We found that there were no significant systematic errors until the X location of the ideal charge was less than 0 km or greater than 35 km (See Figure 1). Standard deviations of the X-Y position errors were less than 1.5 km over the entire study area and were less than 1 km over most of this area.

CASE STUDIES

JULY 21, 1988: This storm produced the most lightning in the study area. A line of thunderstorms associated with a sea-breeze convergence moved from the mainland of Florida into the study area around 1845Z (1345L). Several areas of activity developed, but most of the lightning identified by the FM network occurred in two areas. The first was to the west of FM site 18 over the Indian River between 1900Z and 1920Z. The second began near FM site 15 to the southeast of the Shuttle Landing Strip between 1920Z and 1940Z. Altogether, the FM network detected 951 lightning events between 1700Z and 1955Z when the data ended. The LDF detected 312 CG flashes in the study area in the same time interval. Of these 312 CG flashes, 279 (89%) were coincident with FM events. Of the 38 which were not detected by the FM network, 18 were within 1 second of another LDF flash and hence were probably missed by the FM analysis algorithm. We were able to derive 34 satisfactory monopole fits to the FM events and 72 dipole fits. 30 of the monopole fits coincided with an LDF event. Figure 2 shows the X-Y location of all acceptable monopole and dipole fits for 7/21/88, and Figure 3 shows the locations of all LDF events. Figure 4 shows explicitly the horizontal separation between the locations provided by each system for the coincident lightning events.

JULY 22, 1988: There were two main areas of convection on this day; the first occurred southwest of FM site 10 between 1840Z and 1900Z. Here, the FM events produced 7 dipole solutions while the LDFs located two CG strikes. The second cell developed northwest of FM site 1 between 1900Z and 1930Z, and there were 22 LDF events in this interval. There were 111 FM discharges between 1835Z and 1940Z. All of the 24 LDF flashes in the study area were coincident with a FM event. Of the 24 CG flashes, 17 fit the monopole model. One CG flash was best fit by the dipole model, and the dipole moment of this flash was nearly horizontal. Figure 5 shows a map of the locations of all acceptable monopole and dipole fits for 7/22/88. Figure 6 shows a map of the LDF events, and Figure 7 shows the horizontal separation for coincident events.

AUGUST 9, 1988: Most activity on this day was west of FM site 7, and there were 61 FM flashes between 1830Z and 2015Z. There were 20 LDF flashes in this interval and 18 were coincident with a FM event. In the cases where the FM network did not detect a LDF flash, both were within 0.5 seconds of another LDF flash. 8 of the LDF flashes provided satisfactory FM solutions. 15 FM events fit the monopole model and 9 fit the dipole model. Figure 8 shows a plot of the locations of FM events on 8/9/88. Figure 9 shows all LDF flash locations and Figure 10 shows the horizontal separation between the coincident flashes.

DISCUSSION

The FM network was able to detect over 90 percent (321 of 356) of the CG flashes that were detected by the LDFs on all three days. When an LDF event was missed, 20 (of 35) occurred within 1 second of another LDF event. If we assume events that occur within 1 second of each other produce a single change in the electric field, 95 percent of the CG events were detected by the FM network. This assumption is reasonable since the sampling rate of 5 samples per second may not be sufficient to resolve 2 lightning flashes within a one second period. Altogether, 28 percent of FM lightning events were coincident with a CG event detected by the LDFs. This is a reasonable fraction of CG lightning at KSC [13].

On the above three storm days, we were able to fit 56 FM solutions that were coincident with an LDF location; i.e., about 17 percent of all the CG flashes. In addition, 17 percent of all FM events could be fitted satisfactorily within the limits imposed by our acceptance criteria. The percentage of satisfactory fits varied significantly on the different days: 11 percent on July 21, 31 percent on July 22, and 43 percent on August 9.

Figure 11 shows a histogram of the differences in the horizontal distance between the projected charge center and the LDF ground strike points for these 56 flashes. Note that these differences include errors in both detections systems and that 95% of the values are within 12 km, 75% are within 8 km, and 50% within 4 km. These results are somewhat larger than the horizontal variations found by Jacobson and Krider [5], where 95% were within 8 km and 75% were within 5 km. It is interesting to note that one of the differences in this study exceeded the 18 km (10 nm) launch criteria.

The average X,Y and standard deviation (in parenthesis) of the coincident FM and LDF locations are shown in Table II for each storm day. For the July 21 storm, we are showing only the 19 flashes in the Banana River cell with X parameters between 0 and 10 km and Y parameters between 10 and 22 km. The 17 events north of FM site 1 are used for the July 22 storm, and all 8 events are used for August 9.

TABLE II: AVERAGE LOCATIONS FOR STORM DAYS

DATE	AVG X FM(km)	AVG Y FM(km)	AVG X LDF(km)	AVG Y LDF(km)	ΔX (km)	ΔY (km)
7/21	8.4 (2.2)	17.1 (2.4)	7.8 (1.6)	19.6 (3.3)	0.6	-2.5
7/22	15.5 (1.2)	36.8 (1.1)	9.9 (3.5)	38.9 (2.1)	5.6	-2.1
8/9	6.0 (0.6)	31.8 (1.9)	6.1 (2.0)	33.4 (3.5)	-0.1	-1.6

Note that the differences in the average X and Y coordinates are about what one would expect, given the errors in the measurements and the above standard deviations, except for a 5.6 km shift in the X position on 7/22/88 (see Fig. 7). We have checked for possible systematic errors in both the LDF and FM locations in this storm region and have concluded that this shift is, in fact, real and not an artifact. Note also that the standard deviations in the FM locations are about 50 percent less than the standard deviations in the LDF locations in the small storms on July 22 and August 9.

CONCLUSIONS

We estimate that the detection efficiency of the FM network is between 90 and 95 percent on lightning in the study area, assuming that the LDF network detects all negative CG flashes. The FM network detects many more lightning events than the LDF network because the FMs also detect intra-cloud lightning. Only 17 percent of the FM events could be modeled (monopole or dipole) using a fairly strict set of rejection criteria. This percentage varied on the three storm days and was significantly higher on days with low flashing rates. Therefore, the utility of the FM network would appear to be limited by modeling requirements rather than by its ability to detect a lightning event.

In most cases, when the FM network missed a CG discharge, it was because there were two LDF flashes within 1 second of each other, an interval that exceeded the time resolution of the FM network.

The distribution of the horizontal distances between the FM charge centers and the associated LDF locations have been summarized in Figure 11. The largest cause of these distances is undoubtedly the quasi-random 'stepped' development of the initial leader channel from the 7 or 8 km altitude of the cloud charge [8] to the ground. These distances also include a random error in each detection network that is on the order of one kilometer. The large system shift that we have noted on 7/22/88 (see Table II) may well have been caused by a preferred direction of propagation that was introduced perhaps by the meteorological structure of the storm or a preferred region in the cloud for lightning initiation. In any case, the variability shown in Fig. 11 suggests that the 10 nm (18.5 km) 'stand-off distance' in the present launch rules is indeed safe.

Since the standard deviations of the FM locations under small storms tend to be less than the LDF positions, such locations might provide a better estimate of the source of lightning in the cloud. For example, the launch criteria could possibly say 'within N nm of the lightning charge center' rather than 'within 10 nm of lightning', since the FM charge centers provide the locations of developing charge rather than where channels actually strike the ground. More data will be needed to determine what distance is optimum for a threat radius for each detection system. In the future, we plan to continue studies such as this with other meteorological information, such as the surface wind divergence and weather radar data.

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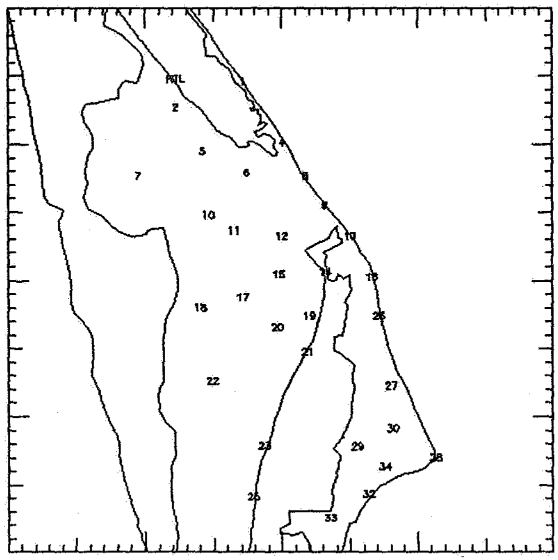

Figure 1- Locations of the Field Mills (1-34) and the Rocket Triggered Lightning Site in 1988. The lower left hand corner is the origin of our coordinate system. Each tick mark is 1 km.

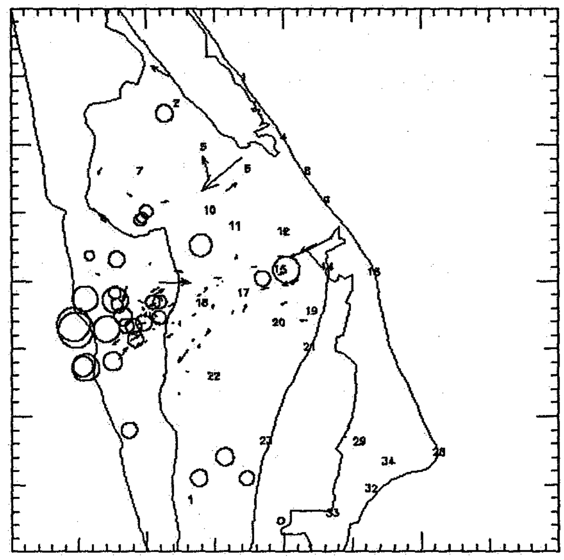

Figure 2- Monopole (circle) and dipole (arrow) fits for July 21, 1988. The location of FM sites with bad data are not plotted on this and similar figures.

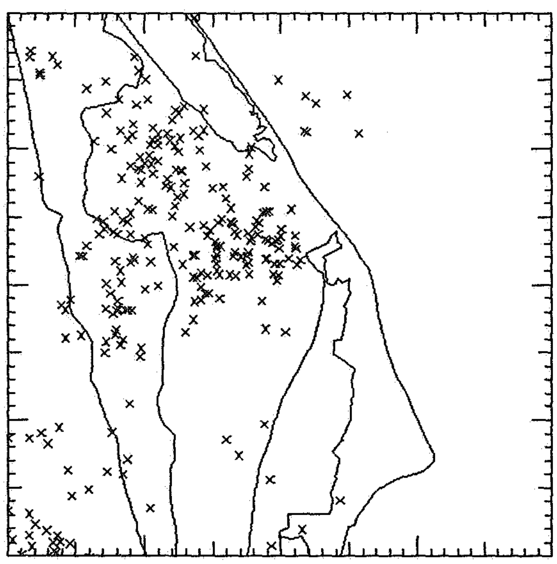

Figure 3- Locations of LDF lightning events for July 21, 1988.

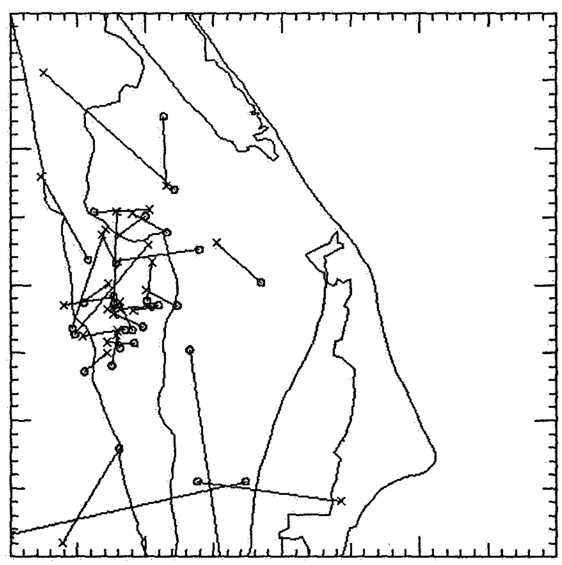

Figure 4- Horizontal separation between coincident FM (circle) and LDF (crosses) events for July 21, 1988.

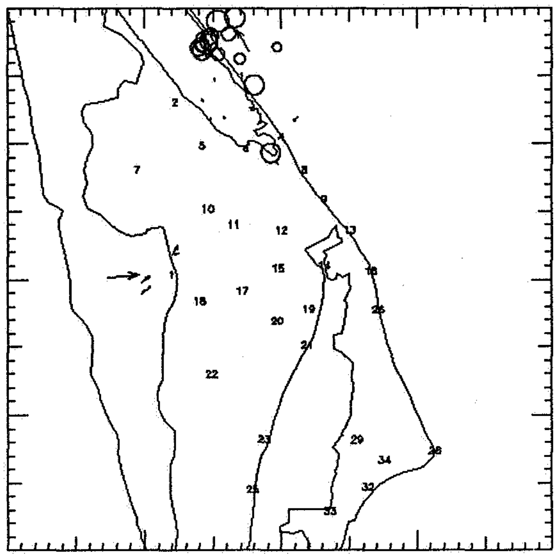

Figure 5- FM fits for July 22, 1988.

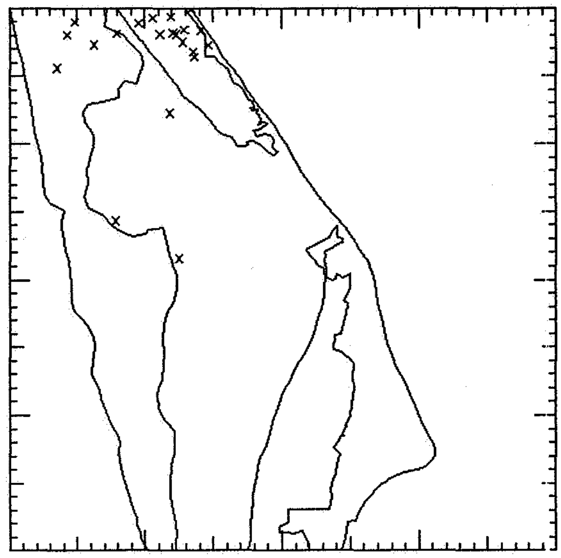

Figure 6- LDF flashes for July 22, 1988.

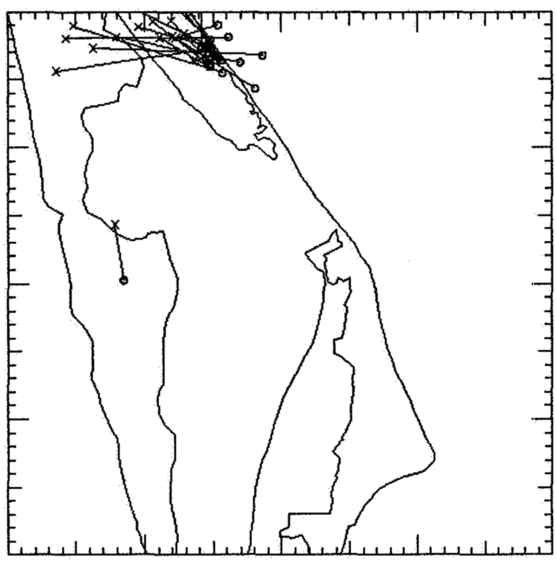

Figure 7- Horizontal separation between coincident FM and LDF events for July 22, 1988.

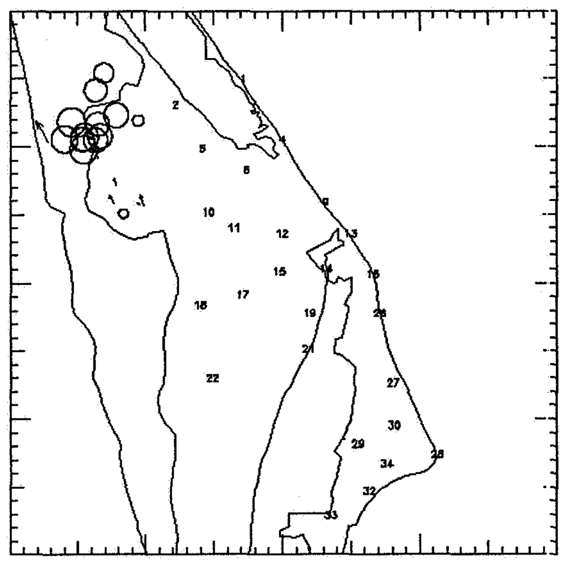

Figure 8- FM fits for August 9, 1988.

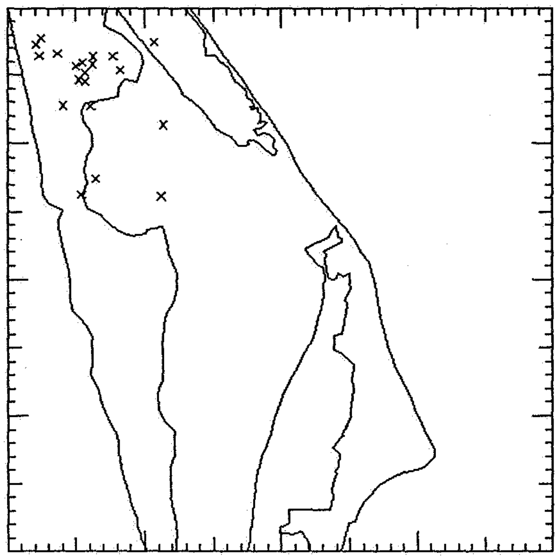

Figure 9- LDF lightning events for August 9, 1988.

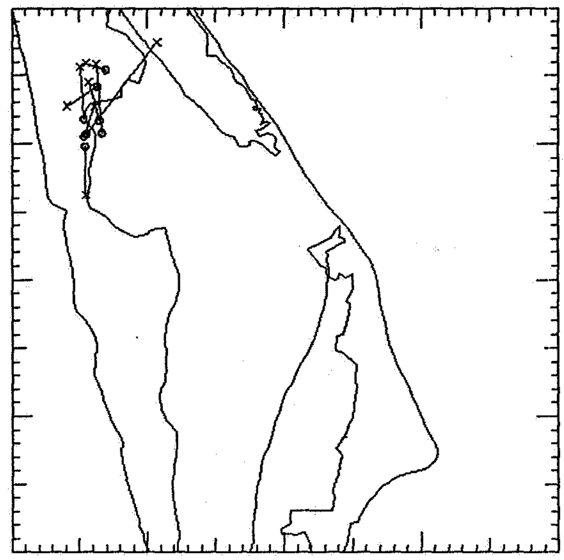

Figure 10- Horizontal separation between coincident FM and LDF flashes.

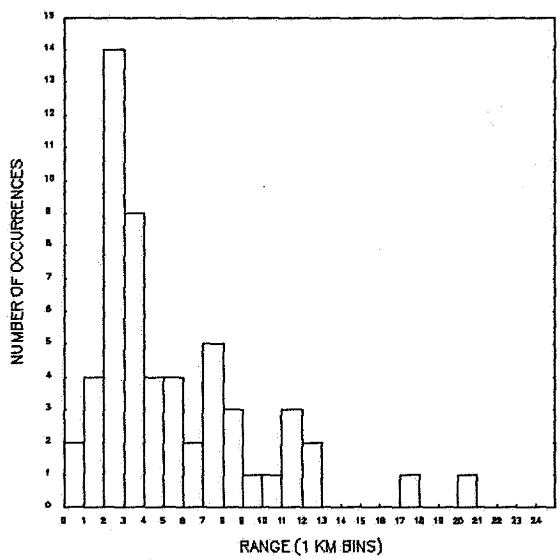

Figure 11- Histogram of horizontal differences between coincident FM and LDF flashes.