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ANALYSIS OF SURFACE ELECTRIC-FIELD CONTOURS IN RELATION TO CLOUD-TO-GROUND LIGHTNING FLASHES IN AIR-MASS THUNDERSTORMS AT THE KENNEDY SPACE CENTER

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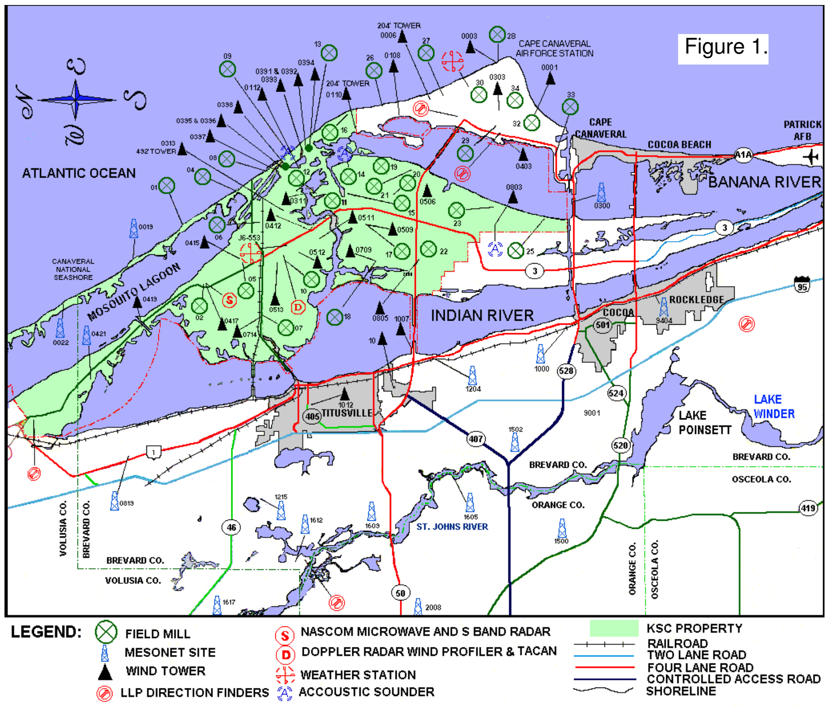
1. INTRODUCTION

A recent study by Lengyel (2004, 2005) showed that more than half of lightning casualties resulted from the first or one of the first few cloud-to-ground (CG) flahses in a storm and that significant numbers of casualties resulted from returning to outdoor activities too soon, before lightning had actually ceased. The motivation for this study has been to see if the temporal evolution of contours of surface electric field can be used to provide objective guidance in support of lightning hazard-warning decision processes in those kinds of situations. The network of electric-field meters at the Kennedy Space Center (KSC) and the adjacent Cape Canaveral Air Force Station (CCAFS) currently comprises 31 conventional electric-field mills distributed over an area of approximately 650 square miles as shown in Figure 1. Data from the network are continuously recorded and archived. For this study we have analyzed contours of surface electric field from archived sets of field-mill data from the network for three storm seasons in an attempt to elicit patterns relevant to the occurrence of CG lightning flashes. Although both IC and CG lightning are of great concern at KSC/CCAFS, we began our investigation by focusing on CG flashes since for most lightning hazard-warning situations it is CG lightning that is of most concern to decision makers. Because isolated, air-mass, or "pulse" thunderstorms are the most likely type to develop directly over an area of concern (AOC) and to produce a first CG lightning flash within the AOC, we have limited our investigation to such storms.



2. THUNDERSTORM SELECTION

We chose to limit the study to the period between May 1 and September 30, which encompasses the majority of the warm season in central Florida, and represents the most active time of the year in Florida for pulse thunderstorms. These storms develop fairly rapidly (on the order of tens of minutes) and often develop while showing very little evidence of their onset in surface observations. For example, they do not form on or follow a baroclinic boundary that can be easily detected by means of conventional observational data. However, these storms often form on low-altitude weak boundaries such as sea breeze fronts, river breeze fronts, convective outflow, etc., and especially on intersections of two or more of these boundaries. We chose to use data from years 2004 through 2006, a period for which archived electric-field data were readily available, and further, we limited our scope to the period of time between 12:00 PM and 6:00 PM local time because pulse thunderstorms most often occur in the early to late afternoon during and just following the maximum positive net insolation and heating of the surface. In order to identify thunderstorms that fit the pulse criteria, we used KSC/CCAFS rainfall and CG lightning data first to identify days when there was either lightning observed somewhere within the Cloud-to-Ground Lightning Surveillance System (CGLSS) network, or rainfall over KSC, or in many cases, both. The CGLSS data, which are accurate to within 250 m, were analyzed and the times of all CG flashes between 1200 and 1800 EDT were noted. In a similar manner, the KSC/CCAFS rainfall data set was analyzed for the timing of rainfall over KSC/CCAFS. Hourly rainfall data are reported from most of 31 field-mill sites. We noted the occurrence of any rainfall at any site at any time between the hours of 1200 and 1800 EDT.

Then, on the basis of rainfall and CG data, we chose days for which to create animations of radar data in order to determine the nature of the storms. For each time period on each day that rainfall and/or CG data were recorded, we produced an animation of archived NEXRAD base reflectivity at tilt one (0.5°) from the Melbourne, Florida (KMLB) radar. We examined base reflectivity data for the period from a few mintues before to a few minutes after the time period of rainfall and/or CG data. For example, if rainfall data were recorded from 1200 to 1400, and CG data were recorded from 1300 to 1600, then base reflectivity data from roughly 1155 to 1605 were animated.

Examination of the base reflectivity animations led quickly to identification of the manner in which a given thunderstorm formed. On the basis of that identification, for example, as shown in Figure 2, we determined whether a given case was suitable for our analysis. On many days, there were multiple thunderstorms that moved over KSC. To address the issue of first CG flashes, we wanted to be able to examine the evolution of the surface electric field from fair-weather conditions to the time of the first CG flash. Therefore we limited our attention to first thunderstorms and we assigned a time period to each storm on the basis of its initiation, development, and dissipation or advection out of the AOC, as indicated in the radar animations. In order to be sure that we would not miss the occurrence of a first or last flash, we acquired field data for a period of time starting approximately 30 minutes before the beginning and ending approximatley 30 minutes after end of the storm duration indicated by radar.

3. CG AND ELECTRIC-FIELD DATA

For each case-study thunderstorm chosen as described above, we noted the time and location of the first CG flash that occurred within the KSC AOC. We defined the AOC for this study as a rectangle that includes the lowest and highest latitude and least and greatest longitude of the 31 field-mill sites. We then downloaded electric-field data for the period of 30 minutes before the first flash and 30 minutes after the last flash.

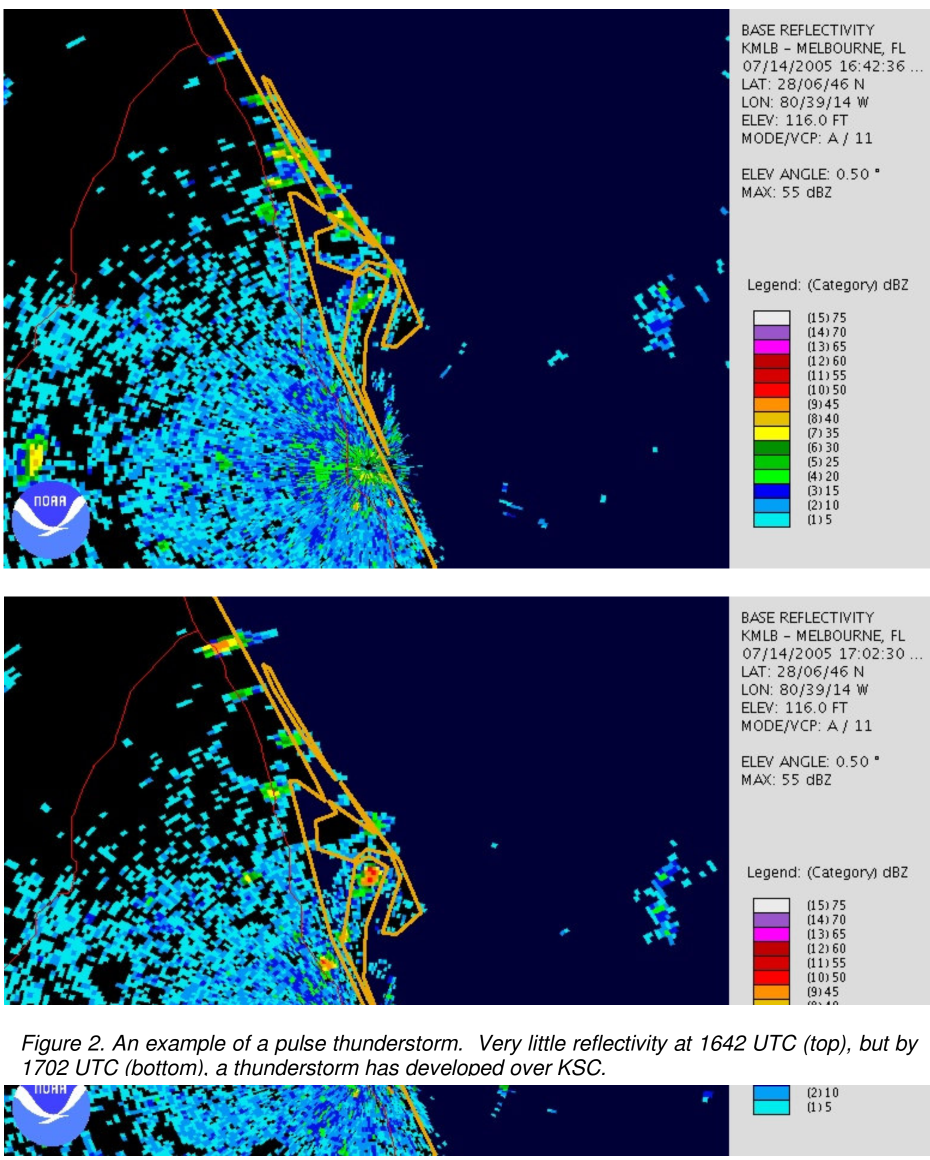


Figure 2. An example of a pulse thunderstorm. Very little reflectivity at 1642 UTC (top), but by 1702 UTC (bottom), a thunderstorm has developed over KSC.

Given that in a 30-minute period there are 90,000 electric-field observations at each field mill, we had to perform averages of the data in order to reduce the files to manageable sizes. Furthermore, most real-world applications may not have the luxury of 50 Hz data that are available from the KSC network, so data averaged over longer periods are in general more realistic for ordniary applications. We arbitrarily chose to average over a period of 20 seconds. That appeared to preserve a reasonable level of temporal detail, while cutting the number of plots for the animations to just 90 per 30 minute time period. For purposes of determining whether Launch Commit Criteria are satisfied, the Air Force 45th Weather Squadron (45 WS) at KSC/CCAFS performs one-minute averages operationally.

If a given field mill was not operational at the start of the 30 minute period, or became inoperable at any point during the 30-minute time period, we did not use the data in the analysis. If all the field mills were not operational for any period of time during the 30-minute time period, then the case study was abandoned for that CG flash.

To generate contours we started by performing a two-pass Barnes objective analysis on the electric-field data. A first pass was computed, a bilinear interpolation was performed to estimate the first pass error, and then the second pass with an updated convergence parameter was computed, taking the estimated error into account. Using MATLAB, a filled-contour plot was produced for each of the 90 objectively analyzed electric-field data periods. Superimposed on the contour plots are the locations of the operational field mills and the CG flash of interest. The 90 such plots were then incorporated in an animation which we studied and analyzed both subjectively and objectively. Snapshots of 4 such contour plots out of a sequence are shown in Figure 3.

4. ANALYSIS

We examined the tempoal evolution of the contours of surface electric field in the AOC leading up to 58 first CG flashes. Visual observations of the animated contours show a large variability in the behavior of the electric field prior to the first CG flash. In a few cases, the electric field remained at fair-weather values (a few hundred V/m negative) up until the time of the flash. In most cases, however, strong gradients in the field appear (indicated by density of contour lines) several minutes before the flash, at distances within 5 km to 10 km from the location of the eventual CG flash. A "couplet" of strong negative and positive electric field regions sometimes develops a few minutes before the flash near the location of the eventual flash, as illustrated in Figure 3.

To get some ideas about how the contour plots could be used for lightning hazard-warning decision support, we ask the following questions.

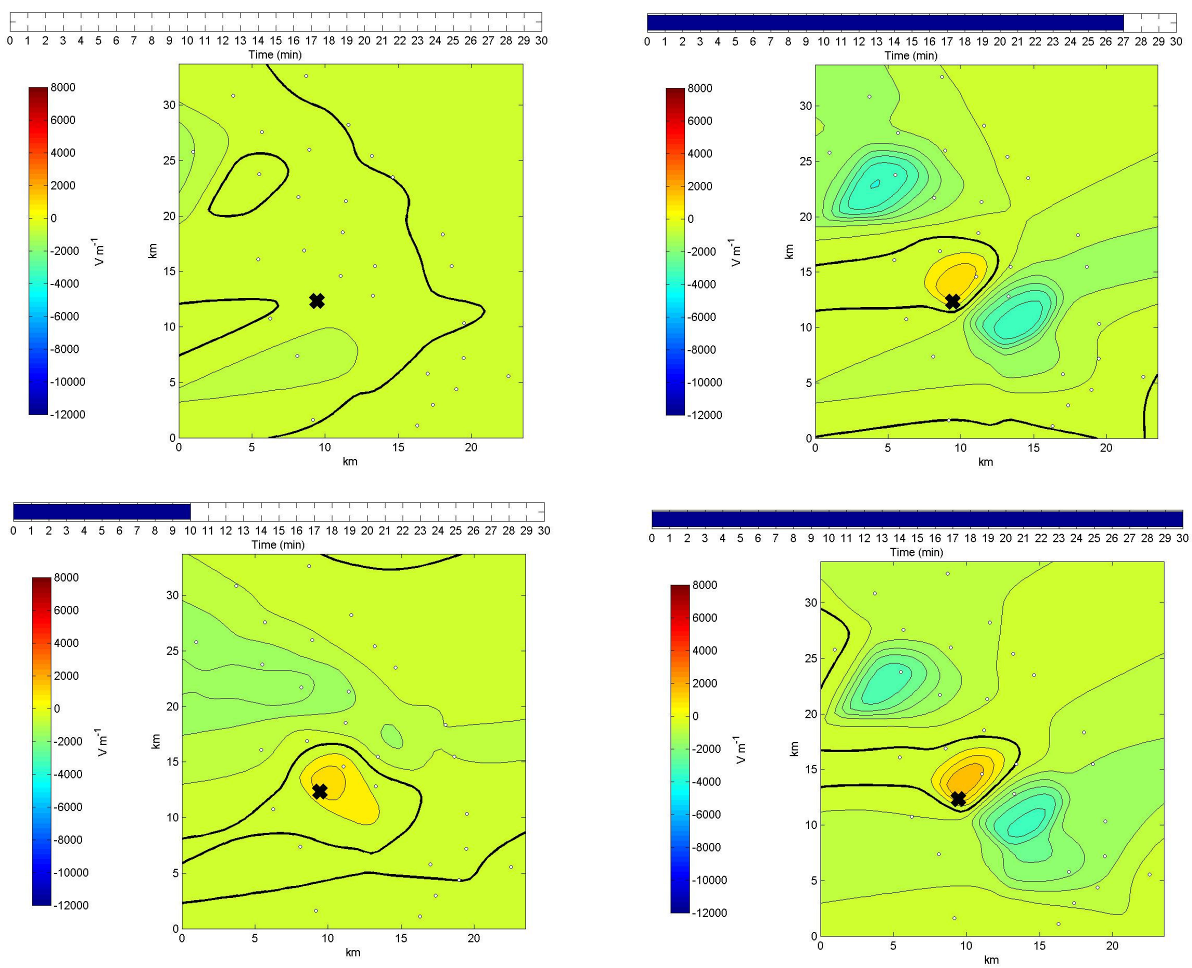


Figure 3. Examples electric-field contour images. The clock starts 30 minutes before the first CG flash, located at the ✖. The first plot is at t = 0 minutes, the second at t = 10minutes, the third at t = 27 minutes and the last at t= 30 minutes, the time of occurrence of the CG flash. The circles represent the locations of the operational field mills. The bold contour is the 0 V/m isoline.

1. In what fraction of first CG cases does the electric field exceed +/- **E** kV/m (E = 1,2,5) within **R** km (R = 10,5,2,1) of the flash location, within **T** minutes inclusive, (T = 10,5,2,1) before the first flash? This gives us an idea of the chance of any warning up to the last minute before the flash.

2. In what fraction of the first CG cases does the field never exceed +/- 1 kV/m within 10 km of the flash location, within 10 minutes before the first flash? This gives us an idea of the chance that there will be a failure to warn, given the network being used.

3. In what fraction of first CG cases does the electric field exceed +/- E kV/m (E = 1,2,5) within R km (R = 10,5,2,1) of the flash location, at times of 12 to 15 minutes, 9 to 12 minutes, 6 to 9 minutes and 3 to 6 minutes before the flash. This gives us an idea of how much advanced warning time might be realizable.

To answer the first question, we automated the procedure to evaluate all 58 flashes (A58 in Table 1). Then we considered only the 49 flashes that occurred within the area defined by the operational field mills (A49 in Table 1). Then one of the authors (PH) performed an inherently subjective visual manual search in order to provide insight as to the potential that an observer could detect trends in real time (M58 in Table 1). The results of these analyses are shown in Table 1. The data in Table 1 should be interpreted as follows. The rows specify radius from the first CG flash location and the columns specify the time period before the first CG flash. The sub-columns specify the % of cases for which the criteria are met by automated search for all cases (A58), cases when the CG is well within the operational network (A49), and cases examined by by manual visual search (M58).

The data in Table 1 show for example that in 81.3% of all 58 cases and in 83.7% of the 49 cases for which the CG strike point was well within the network, the objectively analyzed electric-field magnitude exceeded 1 kV/m within a circle of radius 10 km centered on the flash location, at some time within the 10 minute period prior to the first CG flash. Note that this same percentage applied even for flashes within 5 km. Also we note that reducing the the number of cases to those well within the AOC did not make much difference.

Note that even if one considers a radius of only 2 km from the CG strike point, the field magnitude exceeded the 1 kV/m threshold at some time in the 10 minute period before the CG flash in 77.6% of the cases when the CG was well within the network.

The answer to the second question is implicit in Table 1 and the answer to the first. Clearly if there the threshold was exceeded 81.3% of the time, then in 18.7% of the 58 cases the objectively analyzed electric field did not exceed the +/-1 kV/m threshold within a radius of 10 km during the 10 minute period preceding the flash.

To address question 3, we performed a new analysis on the data sets, examining 50 cases that were well within

Table 1.

+/- 1 kV/m												
	10 min			5 min			2 min			1 min		
	A58	*A49*	*M58*	*A58*	*A49*	*M58*	*A58*	*A49*	*M58*	*A58*	*A49*	*M58*
10 km	81.3	83.7	67.8	75.9	79.6	66.1	75.9	79.6	61.0	72.4	77.6	61.0
5 km	79.3	83.7	59.3	74.1	79.6	59.3	72.4	77.6	57.6	69.0	75.5	54.2
2 km	72.4	77.6	45.7	70.7	75.5	45.7	69.0	73.5	45.7	63.8	69.4	40.6
1 km	62.1	67.3	38.9	58.6	63.3	38.9	58.6	63.3	37.2	53.4	59.2	33.8
+/- 2 kV/m												
	10 min			5 min			2 min			1 min		
	A58	*A49*	*M58*	*A58*	*A49*	*M58*	*A58*	*A49*	*M58*	*A58*	*A49*	*M58*
10 km	56.9	59.2	49.1	56.9	59.2	47.4	51.7	53.1	40.6	46.6	46.9	35.5
5 km	48.3	51.0	40.6	48.3	51.0	38.9	39.7	40.8	30.5	37.9	38.8	23.7
2 km	41.4	42.9	27.1	41.4	42.9	27.1	32.8	32.7	23.7	32.8	32.7	18.6
1 km	32.8	34.7	23.7	32.8	34.7	20.3	27.6	28.6	18.6	24.1	26.5	15.2
+/- 5 kV/m												
	10 min			5 min			2 min			1 min		
	A58	*A49*	*M58*	*A58*	*A49*	*M58*	*A58*	*A49*	*M58*	*A58*	*A49*	*M58*
10 km	6.9	6.1	10.1	6.9	6.1	10.1	1.7	2.0	8.4	1.7	2.0	8.4
5 km	5.2	4.1	6.7	5.2	4.1	6.7	1.7	2.0	5.0	1.7	2.0	5.0
2 km	3.4	2.0	6.7	1.7	2.0	6.7	1.7	2.0	5.0	1.7	2.0	5.0
1 km	1.7	2.0	5.0	1.7	2.0	5.0	1.7	2.0	5.0	1.7	2.0	5.0

the AOC covered by operational field mills. The results are shown in Table 2.

Table 2.

+/- 1 kV/m										
	15-12 min		12-9 min		9-6 min		6-3 min		3-0 min	
	#	%	#	%	#	%	#	%	#	%
10 km	25	50	28	56	33	66	36	72	39	78
5 km	19	38	24	48	29	58	33	66	39	78
2 km	17	34	20	40	20	40	30	60	36	72
1 km	17	34	19	38	18	36	26	52	31	62

+/- 2 kV/m										
	15-12 min		12-9 min		9-6 min		6-3 min		3-0 min	
	#	%	#	%	#	%	#	%	#	%
10 km	13	26	18	36	23	46	25	50	28	56
5 km	8	16	13	26	14	28	20	40	21	42
2 km	6	12	10	20	12	24	15	30	17	34
1 km	3	6	7	14	10	20	11	22	15	30

+/- 5 kV/m										
	15-12 min		12-9 min		9-6 min		6-3 min		3-0 min	
	#	%	#	%	#	%	#	%	#	%
10 km	0	0	0	0	0	0	3	6	1	0
5 km	0	0	0	0	0	0	2	4	1	0
2 km	0	0	0	0	0	0	0	0	1	0
1 km	0	0	0	0	0	0	0	0	1	0

Consider the results in the first two rows of the tables for 1 kV/m threshold. In 78% of cases the thershold was exceeded within a period of 0 to 3 minutes within both a 5 km radius and a 10 km radius. More importantly, though, the threshold was exceeded at 6 to 9 minutes before the flash in 58% and 66% of the cases within 5 km radius and 10 km radius respectively.

5. DISCUSSION AND CONCLUSION

The results in Table 1 show that the electric-field magnitude exceeded 1 kV/m within 10 km of the ground-strike point within 10 minutes before first CG flashes in more than 80% of the cases. This result is consistent with the Weather Launch Commit Criteria at KSC, which prescribe that no launch will be made if the electric field exceeds +/- 1 kV/m within 5 nautical miles (9.26 km) of the launch pad at anytime within the 15 minutes prior to launch.

Looking at the data from the point of view of "failure to warn", Table 1 shows that the first CG occurred with no field exceeding a 1 kV/m magnitude within 10 minutes and 10 km in 16% to 19% of the cases. We noted subjectively that in some cases the field magnitude was very low throughout the 30 minute period preceding the first CG flash. This suggests investigation of threshold levels in certain circumstances.

Note that even if one considers a radius of only 2 km from the CG strike point, the field magnitude exceeded the 1 kV/m threshold at some time in the 10 minute period before the CG flash in 70% to 80% of the cases when the CG was well within the network.

The manual analysis of electric-field thresholds with respect to spatial and temporal proximity to the first CG flash demonstrated that though this method in general will not be as precise as an automated process, as one would expect, it does yield fairly comparable results. It could serve as an alternative to a fully automated system, as an experienced forecaster at KSC would not rely entirely on the electric-field network to make an informed decision with regard to lightning safety. In situations where the electric field does not exhibit a classic pattern or does not meet a particular threshold, a forecaster may recognize a certain pattern or configuration that on previous occasions was followed by a CG lightning, and use that observational experience in the decision-making process.

The most important conclusion to be drawn from this study are is illustrated in Table 2. Consider the top row in the table for the 1 kV/m threshold. It shows that in 72% of the cases, the threshold was exceeded at least 3 minutes before the first CG flash, in 66% of the cases at least 6 minutes in advance, and in 56% of cases at least 9 minutes in advance withn 10 km of the eventual gruound-strike point. For the period of 0 to 3 minutes the percentage was the same for radius of 5 km as for 10 km. However, these data also show that, for example, 34% of the time the threshold was not exceeded within 10 km radius as much as 6 minutes to 9 minutes in advance. Although we did attempt to evaluate the effect of being near the periphery, the result was inconclusive (cf. A58 and A49 in Table 1). We speculate that at least to some degree, failure-to-warn issues may be a result of flashes striking from 10 km or more outside the rectangular AOC we defined, where there are no field meters. Failure to warn will also be affected by threshold, and that should be investigated.

Lowering of thresholds will also likely increase false-alarm rate, one critical aspect of this kind of study that still needs to be addressed. We define false alarm rate as the the number of times that a threshold is exceeded for some length of time over a defined area but no CG flash occurs within a defined radius within a specfied time following the threshold-exceeding event. It turns out to have been more difficult than originally anticipated to automate the process of determining this number. In some situations, the risks associated with the possibility of a first CG flash in the AOC may be so great that a high false alarm rate may be tolerable. However, for many economically practical applications of surface contours of network electric-field data, an understanding of and appreciation for false-alarm rates is likely to be essential.

6. REFERENCES

Kennedy Space Center, 1995. Space shuttle weather launch commit criteria and KSC end of mission weather landing criteria. KSC press release 100-95, available online:
http://www-pao.ksc.nasa.gov/kscpao/release/1995/100-95.htm.

Lengyel, M.M., "Lightning casualties and their proximity to surrounding cloud-to-ground lightning", M.S. Thesis, University of Oklahoma, 2004

Lengyel, Megan M., H. E. Brooks, R. E. Holle, M. A. Cooper, "Lightning casualties and their proximity to surrounding cloud-to-ground lightning" P1.35, 14th Symp on Education, American Meteorological Society, 2005

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