P2.10 ANALYSIS OF SURFACE ELECTRIC-FIELD CONTOURS BEFORE FIRST OBSERVED CLOUD-TO-GROUND LIGHTNING FLASHES IN AIR-MASS THUNDERSTORMS OVER KENNEDY SPACE CENTER

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1. INTRODUCTION

The success of operations at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) is highly sensitive to weather, most especially thunderstorms. Of particular concern are air-mass, or pulse, thunderstorms that develop over the complex, which can show very little sign of development in meteorological data prior to a first intra-cloud (IC) or cloud-to-ground (CG) lightning flash. The lightning produced by these storms not only threatens very complex and expensive machinery, but more importantly, it threatens the lives of those working in these conditions.

The KSC/CCAFS compound covers an area of approximately 650 square miles. 31 electric-field mills are deployed throughout this area (Figure 1). The Atlantic Ocean to the east and the Banana and Indian Rivers to the west border the area.

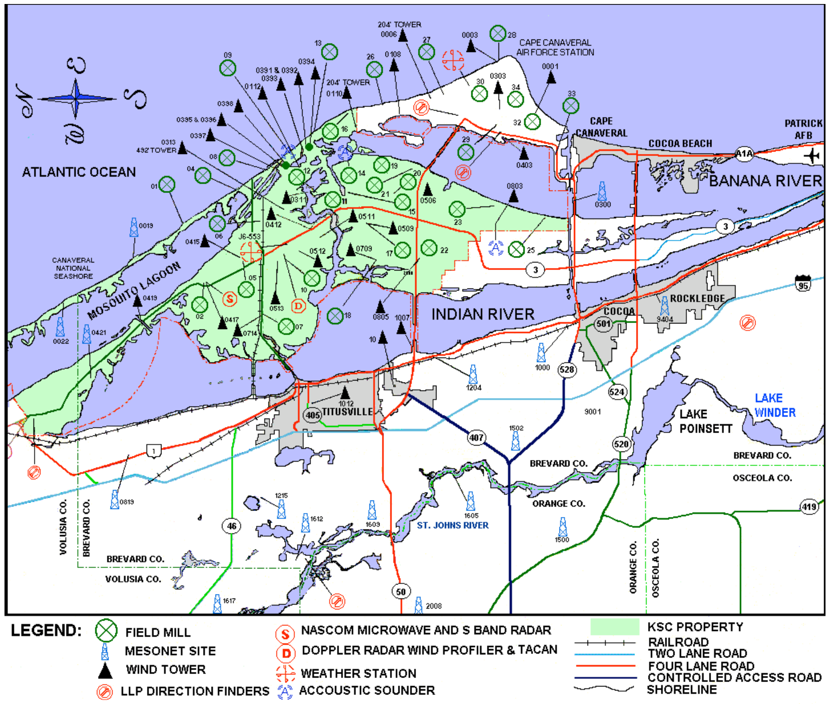

Figure 1. Kennedy Space Center and Cape Canaveral Air Force Station.

Current lightning hazard-warning guidelines are based on the consolidated wisdom of the lightning research community, derived from decades of experience. However, to the best of the authors' knowledge, no current lightning hazard-warning criteria incorporate objective application and interpretation of the temporal and spatial evolution of contours of electric field at the surface before, during, and after active lightning periods in thunderstorms. The authors approached this study with the belief that there is likely to be predictive value in these data.

One motivation for this study is recent research by Lengyel (2004) that showed that in more than half of 106 lightning casualty cases, the victims were struck by one of the first few CG flashes in a storm, or one of the last few CG flashes in a storm. In both cases, knowledge of the electric field at the ground beneath storms is of critical importance to those charged with responsibility to make hazard-warning decisions. In some cases (e.g. NASA/KSC) there is a need to know about the occurrence of first and last IC flashes as well.

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This study analyzes archived data from the KSC/CCAFS electric-field mill network in order to elicit patterns in the evolution of contours of electric field at the surface beneath developing pulse thunderstorms prior to the first CG lightning flash. Future studies will address the issues of first IC flashes, and last CG and IC flashes.

2. PROCEDURE

To identify suitable thunderstorm case studies, the search proceeded as follows.

First, it was decided 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.

"Pulse" here means thunderstorms that develop fairly rapidly (on the order of tens of minutes) and most always occur near the peak in heating of the surface. These thunderstorms often develop while showing very little evidence of their onset in surface observations; i.e., they do not form on or follow a baroclinic boundary that can be easily detected through 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.

Second, it was decided to use data from years 2004 through 2006, a period for which the most reliable electric-field data were available.

Third, it was decided to limit the scope to the period of time between 1200 and 1800 EDT 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.

2.1 *Thunderstorm Selection*

In order to identify thunderstorms that fit the pulse criteria, KSC/CCAFS rainfall and CG lightning data was used 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 timing of all CG flashes between 1200 and 1800 EDT was noted. In a similar manner, the KSC/CCAFS rainfall data set was analyzed for the timing of rainfall over KSC/CCAFS. The rainfall data are reported every hour by the majority of the 31 field mills and give a total amount of rainfall that fell at that mill during the entire hour. If at any time between the hours of 1200 and 1800 EDT rainfall in any amount was recorded at any of the field-mill locations, that time was noted.

On the basis of rainfall and CG data, the authors chose days for which to create animations of radar data in order to examine the nature of the storms. Each day that rainfall and/or CG data were recorded, an animation of archived NEXRAD base reflectivity at tilt one (0.5°) from the Melbourne, Florida (KMLB) radar was created. The reflectivity images are in five-minute intervals. Enough base reflectivity data were used so that the entire time period of rainfall and/or CG data was covered, with a few minutes on either side. 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.

Viewing the base reflectivity animations gave instant feedback on the manner in which a given thunderstorm formed. On many days, there were multiple thunderstorms that moved over KSC, so in order to be able to deduce the maximum amount of information from the surface electric field, one that evolves from a fair-weather electric field to that seen as the first CG flash occurs, only the first thunderstorm was examined. The time of this storm, based on when it developed and dissipated or advected away, was recorded. These times were recorded very liberally; that is, care was taken not to miss a first or last flash, so a generous period of time (on the order of 30 minutes) was allowed before and after the time of the thunderstorm.

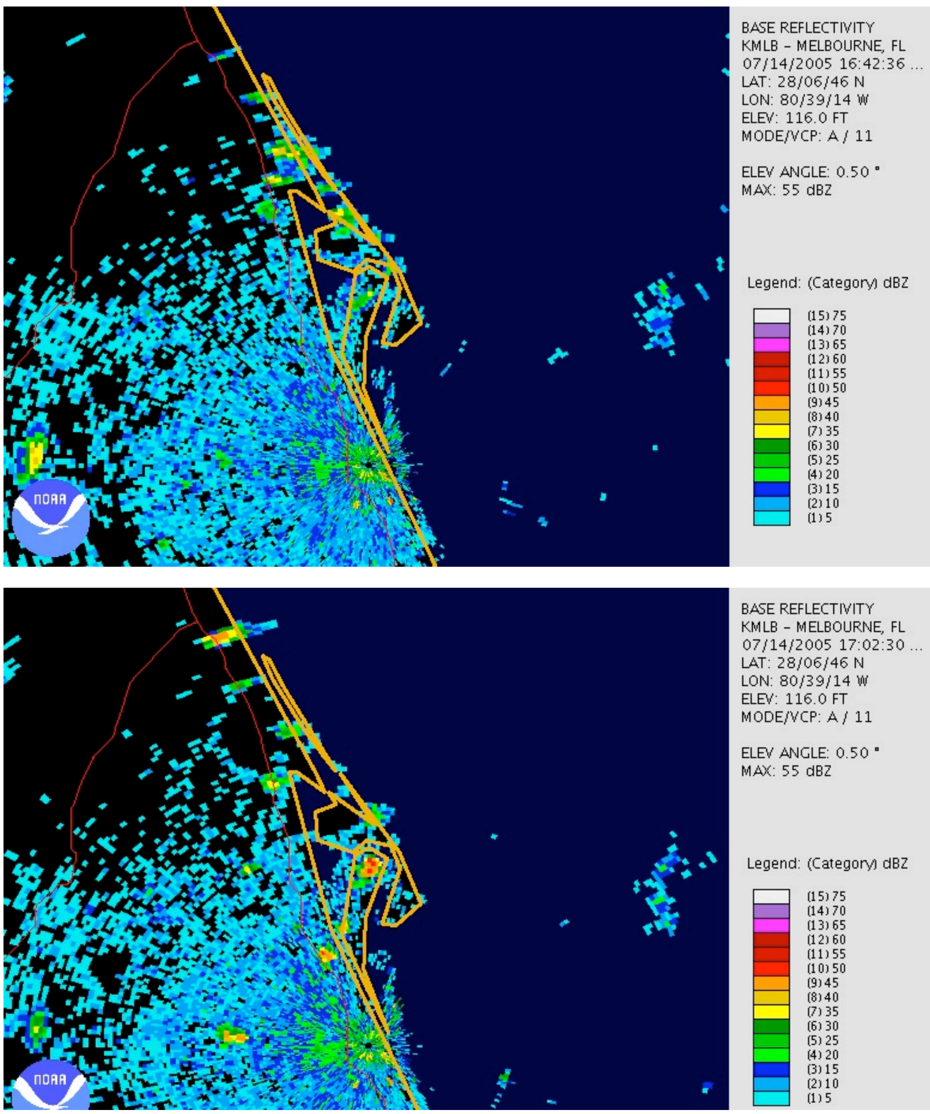

Figure 2. An example of a pulse thunderstorm. Very little reflectivity at 1642 UTC (top), but by 1702 UTC (bottom), a thunderstorm has developed over KSC.

Based on whether or not it fit the pulse criteria, each thunderstorm was determined to be either a suitable storm to examine or one that did not require further examination. An example of a pulse thunderstorm is shown in Figure 2.

2.2 *CG and Electric Field Data*

For each case study thunderstorm, the timing and location of the first CG flash that occurred during the predetermined time of the storm, and within the area defined by KSC, was noted. This area is defined by a rectangle that is shaped by the lowest and highest latitude (east to west boundaries) and lowest and highest longitude (north to south boundaries) of the 31 field mills. Electric field data were downloaded so that exactly 30 minutes before the first flash and 30 minutes after the last flash would be covered. The electric field data are measured at a 50-Hertz sample rate.

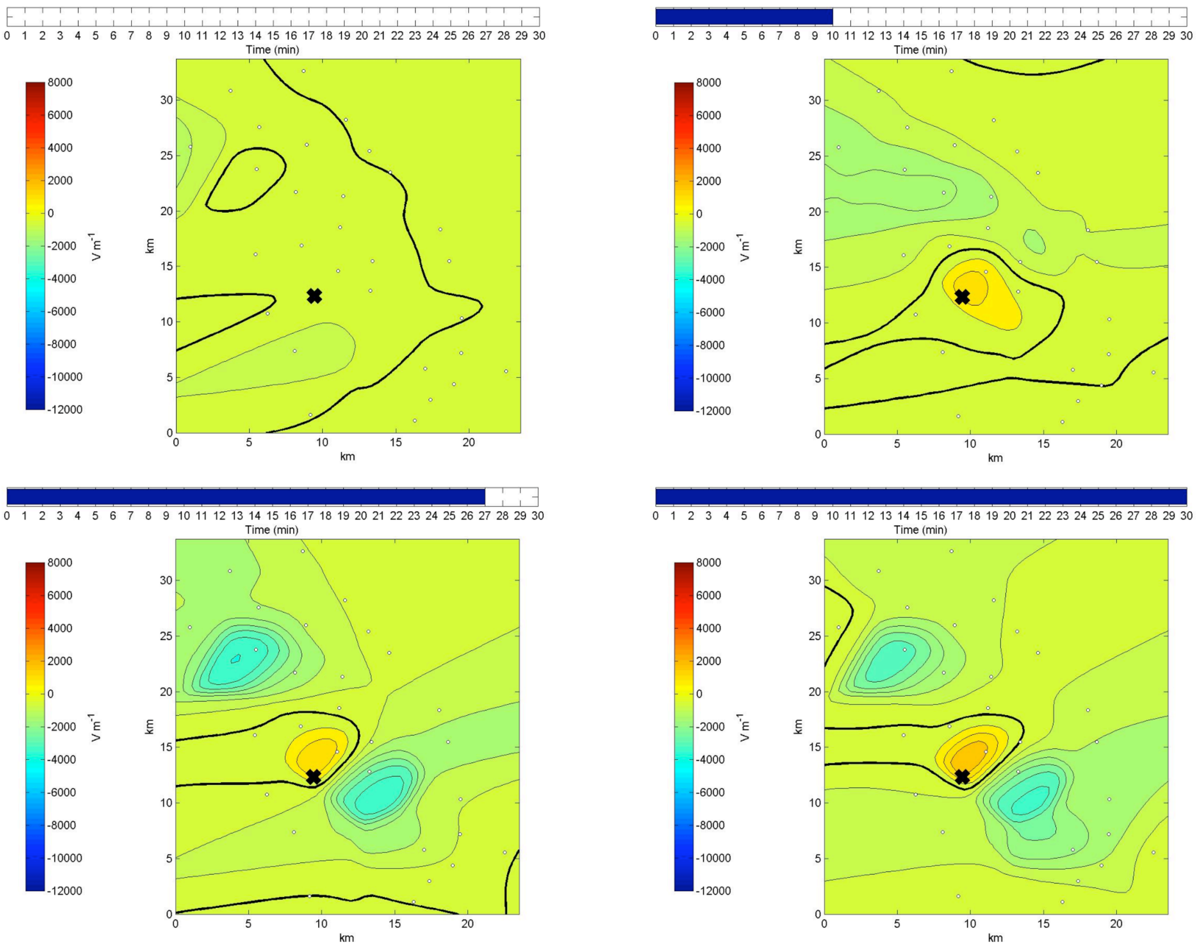

Figure 3. Example electric field contour images from 0, 10, 27, and 30 minutes. 30 minutes is the time at which the flash occurred. The circles represent the locations of the operational field mills and the X the location of the CG flash. The bold contour is the 0 V/m isoline.

Given that in a 30-minute period there are 90000 electric field observations at each field mill, the data needed to be averaged to a much larger time step in order to be able to take a practical look at the field. It was decided that a 20-second time step would be appropriate because it would still show quite a bit of detail temporally but only 90 plots per 30 minute time period would need to be created. The Air Force 45th Weather Squadron (45 WS) uses one-minute averages operationally at KSC/CCAFS, but that is done mostly for evaluating the lightning Launch Commit Criteria, as opposed to forecasting natural lightning.

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, its data were not averaged and not used in the analysis. If all the field mills were not operational for any period of time during the 30-minute time period, then that CG flash was ignored and not analyzed.

A two-pass Barnes objective analysis was performed on the electric field data. A first pass is computed, a bilinear interpolation is performed to estimate the first pass error, and then the second pass with an updated convergence parameter is 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 times. Also plotted were the locations of the operational field mills and the CG flash around which the 30 minutes worth of electric field data is being plotted. These images were animated.

Figure 3 (previous page) shows a sequence of contour images leading up to a first CG flash.

3. RESULTS

58 first CG flashes were analyzed. Visual observations of the animated contours show considerable variability in the behavior of the electric field prior to the first CG flash. In a few cases, the electric field starts at fair-weather values and low gradient, and remains so even up until the time of the flash. In most cases, however, fair-weather fields give way to large fields with strong gradients several minutes before the flash, on the order of 5 km away from the location of the flash. For these flashes, a "couplet" of strong negative and positive electric field often develops adjacent to one another, a few minutes before the flash, at and around the location of the flash.

+/- 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

Table 1. Each sub-table represents an electric field threshold. Each row represents a radius away from the first CG flash, while each main column represents a time period before the flash. Each sub-column represents a different approach to calculating or estimating the percentage of cases for which the threshold is exceeded at that distance and at any time during the period. Table entries are in %.

In an effort to quantify the response in the electric-field contours to an impending first CG flash, two questions were evaluated:

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 (T = 10,5,2,1) before the first 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?

To answer the first question, three approaches were taken. The first was to automate the procedure to evaluate all 58 flashes (A58 in Table 1). The second was to automate the procedure via the computer but considering only the 49 flashes that occurred within the area defined by the operational field mills (A49 in Table 1). The third was for one of the authors (PH) to try to answer this question manually, and inherently in a subjective manner, in order to provide insight as to whether an observer might be able to follow these trends in real time (M58 in Table 1).

The results of these analyses are shown in Table 1. In answer to the first question, in most cases, the first CG flash was preceded within 10 minutes and 10 km by an electric field with magnitude in excess of 1 kV/m. In few cases did the electric-field magnitude exceed 5 kV/m at any time before the first CG flash. For example, looking at all first CG flashes, even those near the edges of the network, 81.3% (column A58, row 10 km) were preceded by an electric-field magnitude in excess of 1 kV/m within 10 minutes and 10 km of the eventual ground-strike. Narrowing it to cases that were (subjectively) well within the network increased that percentage to 83.7% (column A49, row 10 km).

Addressing the second question, note that the result above means that in 18.7% (A58) or 16.3% (A49) of the cases, the field magnitude did not exceed 1 kV/m within 10 km and 10 minutes before the first CG flash. The Weather Launch Commit Criteria at KSC (Kennedy Space Center 1995) prohibit a launch 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. The result presented in Table 1 suggests that even if these criteria are not met, a first CG flash could still occur. This also leaves open the question of whether a launch might actually trigger a flash.

The columns labeled M58 show that the subjective evaluation performed manually followed the same trends, but numbers of cases identifies were smaller throughout. There may be several reasons for this, but the authors surmise that the problems of visual estimations of field values and distances led to under counting.

4. CONCLUSIONS

The fact 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 studied is encouraging. This is in fact consistent with the Launch Commit Criteria. The fact that the first CG occurred with no field exceeding 1 kV/m magnitude within 10 minutes and 10 km in 16% to 19% of the cases suggests that it might be worthwhile to investigate situations in which a lower threshold might be desirable. Indeed, subjective examination showed that in some cases the field was very weak throughout the network. This caused the authors to consider the possibility that the charge accumulation that led to the eventual ground strike in those cases may have been too far outside the coverage of the network to register a strong field. For that reason the analysis was performed again on cases that were subjectively well within the network (the A49 columns in Table 1). The authors also noted that on average, there were 3-5 non-operational KSC/CCAFS field mills at any give time, which in some cases greatly reduced the area covered by the network. When one considers only those flashes that fall well within the area defined by the operational field mills, the percent of cases with a warning signal is slightly improved. This suggests that to increase the likelihood of having a warning signal, the number of marginal cases could be reduced with an expanded network. However, it was surprising to find that the improvement in the prediction by eliminating the marginal strike locations was not that great. This will bear further investigation.

In contrast, a look at the results presented in Table 1 shows that the 1 kV/m threshold was often exceeded within a few km and a few minutes before first CG flashes. Note that inclusion of a larger area in the warning decision region improved the percentages but not by orders of magnitude. Indeed, the difference between 10 km radius and 5 km radius was in some cases insignificant. The authors also noticed subjectively that there were some cases in which the thresholds were exceeded well in advance of the flash time (on the order of 10 minutes) and well away from the flash location (on the order of 10 km), but the strong fields may not have been related to the first CG flash, but instead other CG flashes outside the network or even IC flashes. This will be investigated further.

The manual analysis of electric-field thresholds with respect to spatial and temporal proximity to the first CG flash (A49 columns in Table 1) demonstrated that though this method in general will not be as precise as an automated process, as one would expect, it does yield comparable results. In the hands of an experienced nowcaster, with the benefit of other kinds of data as well, manual visual analysis of field contours in real time could serve as valuable adjunct to a fully automated system. In situations where the electric field does not exhibit a frequently occurring 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 flash, and use that observational experience in the decision-making process.

Finally, in this study the authors have not addressed the false alarm issue. In particular the authors need to determine the number of times that a field contour exceeded a magnitude of 1 kV/m, but that no CG flash occurred within a specified radius during a specified time period. For efficient and effective use of electric-field contours for purposes being suggested, it will be necessary to address this issue. The authors are planning to do this immediate future.

5. REFERENCES

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6. ACKNOWLEDGEMENTS

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