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DEPARTMENT OF COMMERCE
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PRELIMINARY TEST PROGRAM IN CHAFF DISPERSAL WITHIN THUNDERSTORMS AT KENNEDY SPACE CENTER

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Chaff seeding has been successfully used to alter lightning production and intense electric fields in isolated thunderstorms over the high plains of the western United States. Because of the meteorological differences in Florida thunderstorms, a brief (two-week) study of the feasibility of modifying thunderstorms over Kennedy Space Center by releasing chaff was conducted. From this non-statistically configured test, it appears that releasing chaff at the base of Florida thunderstorms will not be as successful as it has been in the West. Furthermore, it may be necessary to use more than one aircraft to release chaff even after the optimum locations for dispersal are known. Recommendations for future studies in the application of chaff seeding to mitigate hazardous electric fields in Florida include the determination of optimum altitudes or temperature levels for chaff release, development of a ground-based instrument to "map" the areas of chaff-produced corona, and the formulation and undertaking of a statistical experiment to determine more accurately the effects of chaff dispersal in these storms.

1. INTRODUCTION

The hypothesis that lightining can be suppressed by seeding electrified clouds has been proposed and described by Weickmann (1963) and Kasemir and Weickmann (1965). Briefly, the technique is based on the physical concept that corona will produce ions near the tips of the chaff fibers in high electric fields. Although an electric field of about 500 kV/m is generally thought to be necessary for the initiation of lightning, fields less than one-tenth of that (30 kV/m) will result in significant corona production by the chaff. In fields above 30 kV/m, the production of ions increases substantially since corona is proportional to the square of the field. The ions that are released in this process are expected to increase the local electrical conductivity within the storm, thus tending to "short-circuit" the storm and inhibit the production of lightning (Kasemir, 1973).

To test the hypothesis, it was proposed to release chaff at the base of thunderstorms. The initial experiments were conducted on moderate-sized, relatively isolated thunderstorms over the high plains of the western United States, mostly in Colorado and Wyoming. The two major findings from these studies are (1) that the electric field at the cloud base decayed about five times faster in seeded storms than in unseeded (control) storms (Holitza and Kasemir, 1974), and (2) that the number of observed lightnings decreased to one-third, or less, of those in the "control" storms (Kasemir et al., 1976). The results of these experiments indicate that electric fields and lightning can be reduced substantially by releasing chaff at the bases of thunderstorms. However, the technique may not be effective in areas that differ in altitude or climate.

During our thunderstorm investigations in June 1975 in support of the Apollo-Soyuz Test Program (ASTP) at Kennedy Space Center (KSC), NASA expressed interest in the use of chaff seeding to reduce the danger of triggered lightning during critical launches. Because of geographic and climatic differences between the high plains and Florida, it was decided that we should perform a brief research study of the feasibility of modifying thunderstorms by chaff dispersal in the KSC area.

This preliminary effort to disperse chaff within electrified clouds was undertaken during the two-week period of 16-27 July 1975, immediately following the ASTP launch when aircraft and ground instrumentation were already in operation. From our recently completed research, during which no chaff was dispersed, it was apparent that the thunderstorms in the KSC area are different from those in Colorado and Wyoming. We noted two major differences: (1) The storms in the high plains that we studied tended to be isolated, often having only a single center of activity, whereas over KSC they were larger, multi-cellular systems; (2) The altitude of the cloud base of thunderstorms in Florida was about 0.6 to 0.9 km, but over the western plains it ranged from 3.7 to 4.9 km.

Repeated cloud penetrations by aircraft are difficult in the larger storm systems in Florida. In addition, it would be difficult to detect the effect of chaff dispersal in a limited region of a large system. The measurements that we had made in June suggested that electric fields near the cloud base in Florida are not as high as they are in the West. It is interesting to note that the freezing level in the summertime is about 5 km for both Florida and Colorado storms, and thus the cloud base in Colorado storms is much closer to the freezing level than it is in Florida storms. The vertical cloud masses are distributed differently, with more than 90 percent of a typical high plains cumulonimbus being above the freezing level compared with about 65 percent for a Florida storm. There is the possibility, however, that the chaff released at cloud base might be entrained in sufficient quantity into the strong field regions of the clouds by turbulence and updrafts. If this were the case, there would be a delay in the reduction of the electric field and lightning.

Although a program of less than 2 weeks would probably not provide definitive information on how best to disperse chaff in Florida, the experience and results of a preliminary program of chaff dispersal would be of value in formulating future thunderstorm research and chaff dispersal programs.

We did *not* configure this program with a statistically randomized operating procedure since the time, and thus the number of storms to be studied, would not have been sufficient. In our attempts to obtain the maximum amount of data on chaff dispersal, we released chaff into all possible thunderstorms at various altitudes within the restricted airspace over the KSC area. This was done without regard to the storms' characteristics, i.e., maximum observed electric field, size, location within the airspace, movement, etc.

2. INSTRUMENTATION AND OPERATIONAL PROCEDURE

Four aircraft were involved in this chaff dispersal program. Three of these were reciprocating twin engine aircraft. They included a T-29, instrumented and operated by NOAA personnel, and the only one of the aircraft capable of releasing chaff; a C-45 (NASA 6) operated by NASA/KSC; and an S2-D carrying NOAA instrumentation and operated by the Naval Research Laboratory. The fourth aircraft, for high altitude measurements, was a Learjet operated by NASA and equipped with rotating-vane field mills by scientists of Stanford Research Institute. Cylindrical field mills of the type developed and described by Kasemir (1972) were installed on the other three.

The chaff dispenser on the NOAA T-29 contained a 10-kg roll of chaff rope consisting of 3000 strands of 25-μm-diameter aluminum-coated fibers. The dispenser cuts the rope into 10-cm lengths, which is a compromise between the electrical advantage of using very long chaff to increase ion production and the operational disadvantage of handling it. The fibers are released at a rate of about 10^7 per minute (0.9 kg/min). According to the manufacturer, at least one-tenth, or 10^6 fibers per minute, are dispersed as individual fibers; i.e., the others may cluster into bunches.

In addition to the aircraft, the program was supported by the KSC weather office from which a NOAA scientist guided the aircraft within restricted air space R2902. A display derived from a network of 25 ground field mills was also located in the weather office. This system provided a map of the equipotential gradient lines at the ground and served to help locate approximate areas over which the highest electric fields would be expected.

Typical chaff seeding operation entailed activating the aircraft, which were based at Patrick Air Force Base located 25 km south of KSC, when conditions were such that thunderstorms over KSC were anticipated. The aircraft entered R2902 at pre-assigned altitudes and were then directed toward the developing or most intense electrical activity as determined from the field-mapping display. Two NOAA scientists were on board the T-29, the lead aircraft. One monitored the instrumentation and chaff dispersal while the other served as the observer and helped choose likely clouds and flight tracks in coordination with the third NOAA scientist directing the mission from the KSC weather office. After an appropriate flight path was selected, the other aircraft generally followed the same track at different altitudes. The flight paths were modified as interpretations of the data and the development of the clouds suggested.

In our previous work, we had released chaff only when electric fields were in excess of 50 kV/m. In this program, however, chaff was dispersed within the storm regardless of the strength of the field measured by the seeding aircraft (the T-29). This was done both because of the short time available and because of our desire to determine whether chaff would be entrained into areas of higher electric fields. To ascertain the existence of corona production from the chaff, a microwave radiometer was used on board the T-29. Since this airborne, corona-detecting instrument was viewing the chaff from within, as seeding occurred, rather than from a distance outside the cloud as had been done during our earlier studies (Rust and Krehbiel, 1977), the capability to detect areas of corona was severely hampered. In general, we released as much chaff as operating conditions permitted. A summary of the chaff dispersal is given in Table 1. The reader should note that the storms involved almost always were not isolated cells.

3. RESULTS

The data obtained during this program were examined to ascertain whether there were any effects on these large, complex storms obviously due to the chaff. The following were studied: electric field mappings at the ground; chaff release tracks in relation to radar echo returns; a coarse determination of the electric fields at different altitudes; the frequency of occurrence of lightning flashes; and indications of corona from the dispersed chaff.

3.1 Field Mappings

As may be seen in Table 1, there were no isolated thunderstorms that remained over the field-mill network. This made the ground field mapping difficult to use in the determination of the effects of the chaff in a small area, since the mapping depicts the net effect of a whole system. As expected, an examination of the field mappings for the various days showed instances of apparent field reduction after chaff releases and others where no such reduction is seen. At this time, there are no generalized conclusions as to the effectiveness of the field mapping as a monitor of the effects of chaff dispersal.

3.2 Chaff Release Flight Tracks

The flight tracks of the chaff-dispersing aircraft, as determined by the observers on board, and the PPI (Plan Position Indicator) echo scans, at an elevation angle of 3 degrees, from the X-band radar operated by the KSC Weather Office, were used to estimate the locations of the chaff releases

Table 1. Summary of Chaff Dispersal Within the KSC Restricted Airspace, R2902, During July 1975

Date 1975	Interval of Chaff Release (GMT)	Chaff Dispersed (kg)	Alt. (km)	Remarks
18 Jly	1520-1537	7.4	2.1	Thunderstorm, not isolated; chaff dispersal in two sections of storm line 33 km long.
	1605-1609	3.3	2.1	Last run after 30-min delay not considered as part of earlier run because of storm movement and echo change.
19 Jly	1751-1824	11.7	2.1	Cell located on southern end of line of cells 28 km long.
22 Jly	1902-1929	5.6	3.0	Large system; line of cells 30 km long; fields $\geq$ 1 kV/m over
	1940-1952	6.5	0.6	all of R2902; chaff released at two altitudes.
25 Jly	1800-1802	2.0	0.6	Edge of storm in SW corner of R2902; storm moved rapidly to W; chaff released in cloud base on eastern edge; chaff release stopped when cloud moved out of R2902.
26 Jly	1849-1921	7.6	0.6	In edge of isolated thunderstorm in SW corner of R2902; chaff released in cloud base; storm propagated outside of R2902.

relative to the thunderstorms. Figure 1 was produced from the overlays made by the radar observer during the flights. Approximate aircraft tracks along which the chaff was released are shown as broad, vertical lines. Chaff was dispersed only within clouds; the apparent clear air portions of the tracks are probably in regions of the clouds not having radar returns or reflect inaccuracies in the estimates of aircraft position. The hatched echo envelopes represent the maximum extent of the echo boundaries during the time period in which the chaff was dispersed. (There are no radar data available for 25 July, but the storm was in R2902 for only a few minutes.) In addition, the observed maximum heights for several of the turrets of each storm are shown. It should be emphasized, however, that these may not represent all the turrets that existed in the cloud system or the true maximum heights. As was expected, the chaff-release area was always much smaller than that of the cloud.

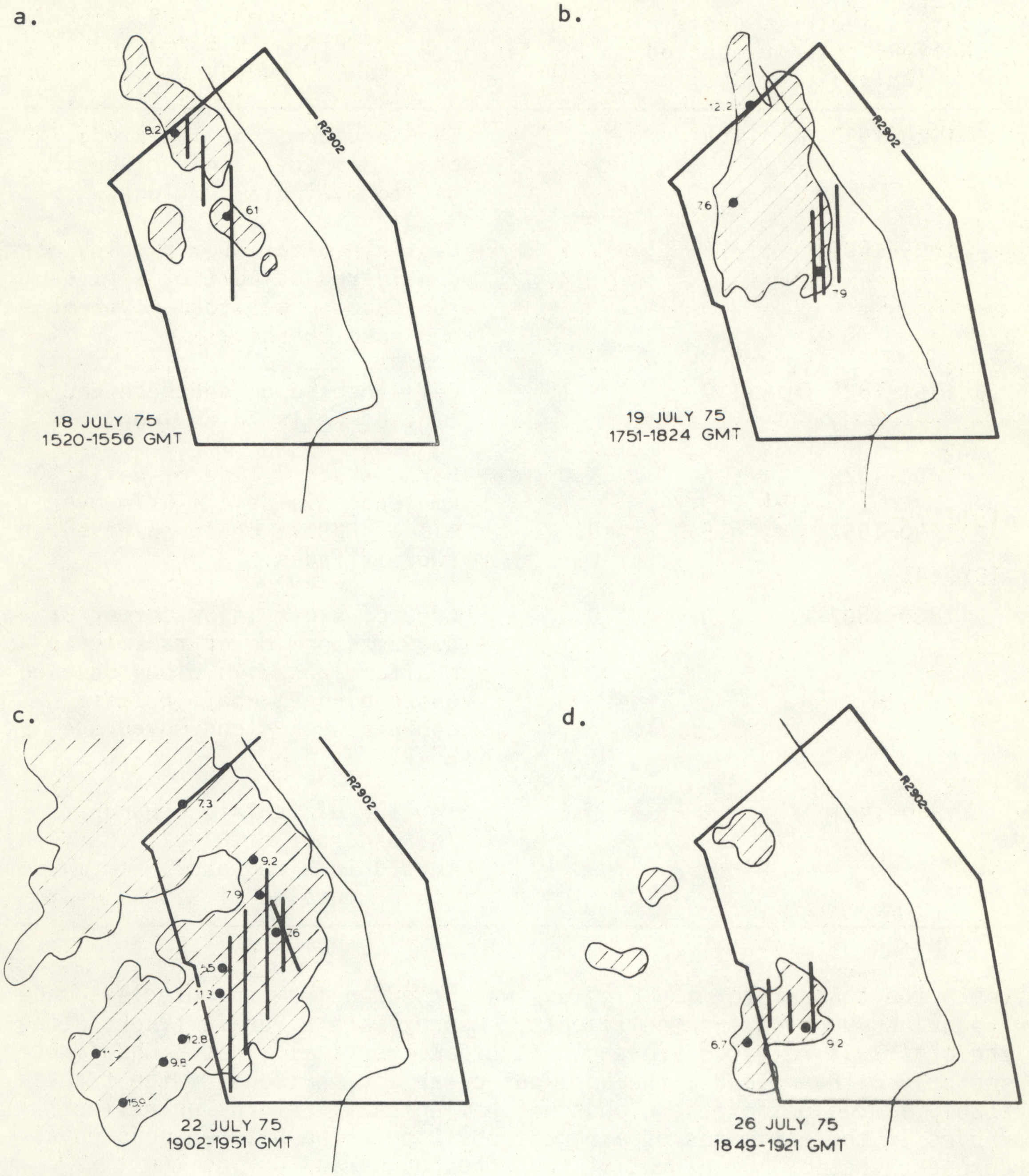


Figure 1. PPI echo envelopes (hatched areas) and approximate flight tracks of chaff-dispersing aircraft (broad, vertical lines) within R2902. Turret locations are denoted by a ● ; the nearby numbers are the maximum observed turret heights in km.

3.3 Electric Fields at Three Altitudes

From the available data, the vertical components of the electric field at three altitudes were determined for several occasions when the flight tracks brought the aircraft over the same grid point within a reasonably short time (Tables 2 and 3). The data from higher altitudes, usually above 6.1 km, are not included here since it is the fields near the altitudes of chaff release that are most significant in determining what effect the chaff had.

Table 2. Vertical Potential Gradients, Gz, for Approximately the Same Grid Points in R2902 and the Same Times During 22 July 1975

Approx. Time (GMT)	Gz (kV/m) at Gnd (0 km)	Lower A/C Alt (km)	Gz (kV/m)	Upper A/C Alt (km)	Gz (kV/m)
1908	-2	0.8	-3	* 3.1	-4
1912	-4 +2	0.8	-10	* 3.1	-34
1924-27	-4	0.8	-10	* 3.1	-22
1941	-1 -6, max.	* 0.6	-4	1.5	-1
1948	-1 -4, max.	* 0.6	-0.2	1.5	-7
1956	<-1 -6, max.	* 0.6	-0.2	1.5	-9
2003	-2 -5, max.	* 0.6	-4	1.5	-4
2005	-1 -6, max.	* 0.6	-7	1.5	-8
2009	-3	* 0.6	-10	1.5	-50
2010-13	-6	* 0.6	-15	1.5	≥ -50
2031	-5	* 0.6	-15	1.5	-24
2036	-7	0.6	-20	1.5	-48

Note: Negative charge overhead is -Gz.
* Denotes the altitude at which chaff was released.

During the flight on 22 July, we initially released chaff at 3.1 km. We then made our first attempt in Florida at dispersing chaff at cloud base. The storm system was quite large (see Table 1 and Figure 1c).

Table 3. Vertical Potential Gradients, Gz, at Three Altitudes on Several Days

Date	Approx. Time (GMT)	Gz (kV/m) at Gnd (0 km)	Lower A/C Alt (km)	Gz (kV/m)	Upper A/C Alt (km)	Gz (kV/m)
19 Jly 75	1700-3	0	0.6	-0.4	2.1	-8
	1725	+2 -0.6	0.6	-10	2.1	-30
25 Jly 75	1804	-0.4	* 0.8	-3	3.1	-5
	1813	-0.8	* 0.6	-4	3.1	-7
	1817	-1	* 0.6	-3	3.1	-50
26 Jly 75	1849	-3	* 0.6	-3	3.1	>-10
	1901	-5 +5	* 0.6	-21	3.1	>-10
	1907	+0.6 -1	* 0.6	+28	3.1	-100

Note: Data were obtained as the aircraft flew over approximately the same grid coordinates at about the same time.
Negative charge overhead is -Gz.
*Denotes the altitude at which chaff was released.

The data presented in Tables 2 and 3 contain several interesting facts: (1) the field at the ground is usually less than the field aloft over the same grid point; (2) the polarity of the field at the ground can reverse within only a few kilometers, e.g., 22 July at 1912 GMT, and 19 and 26 July; and (3) the electric field at cloud base even from large thunderstorms is apparently too low for effective corona production. This last point is significant, for it indicates that in Florida we may not obtain the dramatic results of chaff release at cloud base that we had over the high plains of the West.

4. FREQUENCY OF OCCURRENCE OF LIGHTNING

Although it is a reduction in the electric field itself and not just the suppression of lightning that is the primary objective of chaff dispersal at KSC, a decrease in lightning does imply a decrease in the electric field. It is, then, of interest to determine what effects the dispersed chaff appeared to have on the lightning flash rate. We say "appeared to have" since more cases of both seeded and control storms would be necessary for definite conclusions. Another problem is that the storms studied consisted of several active cells or were near other thunderclouds. For this reason, the lightning-transient data from the field mills, which record lightning field changes essentially omni-directionally, must be interpreted with care.

The frequency of occurrence of lightning was determined for the smaller, more isolated storms of 19, 25, and 26 July, using the records made aboard the T-29. The storms of 25 and 26 July were not as large as the one on 19 July; they also were not part of a long line of cells although they contained more than one distinct, active region. Figures 2-4 show the number of lightnings per five minutes that were recorded on the chaff-dispersing aircraft.

Chaff was released only for about two minutes on 25 July (Figure 2) before the thunderstorm moved out of the southwest corner of R2902. The T-29 continued to monitor the storm, but no additional chaff could be released. Figure 3 shows the occurrence of lightning on 26 July, over about the same location. There are notable features in the data from the two days: (1) On the 25th there is an interval of 15 minutes, beginning about 10 minutes after the chaff was released, when no lightning was recorded; (2) there was more lightning on the 26th; (3) there is a decrease in lightning while chaff was being released on the 26th; and (4) there is an increase in lightning after the last chaff drop on the 26th that might have been from the development of a new cell. (We have not observed this increase in the isolated storms in the West.)

Figure 4 is used to demonstrate more clearly the observations one makes when working a small section of a larger storm system. The chaff was released in the northwest corner of R2902. In addition to the lightning sensed on board the T-29, there is shown in the upper part of the figure the occurrences of lightning from within the cell we were working. These data were obtained with an optical transient detector whose viewing angle was about 3 degrees. We operated this instrument in the KSC weather office. The difference in the number of recorded lightnings is obvious.

The chaff release was begun in this cell when it was still small. It is of interest that although this isolated cell reached a height of at least 7.6 km, there were apparently only a few flashes from it. The chaff releases stopped as the cell began to merge with the larger system, and the mission was soon terminated when flying in the vicinity became too hazardous.

5. DETECTION OF CORONA

As briefly described previously, it is the production of corona at the tips of the chaff fibers that causes the field-reducing and lightning-suppressing effects of chaff dispersal. The measurement of the occurrence of corona is then an indicator of the possibility of a modification effect in a given thunderstorm. We had previously developed a corona detector and used it on board the T-29 during our research in Colorado and Wyoming. The

Figure 2. The number of lightning flashes per 5 minutes recorded on the T-29 for 25 July 1975. Chaff dispersal (denoted 'CHAFF') lasted for only 2 minutes as the storm moved out of R2902. T = 0 is 1800 GMT.

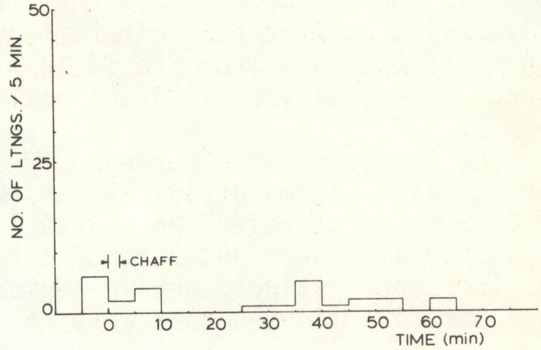


Figure 3. Lightning flashes per 5 minutes recorded on the T-29 for 26 July 1975. The storm was somewhat isolated but contained more than one active cell. T = 0 is 1849 GMT. 'CHAFF' denotes the interval of seeding, although it was not continuous.

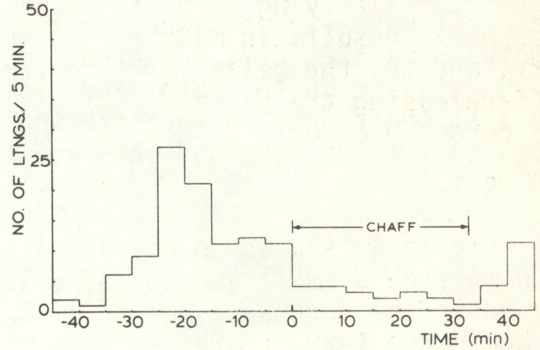
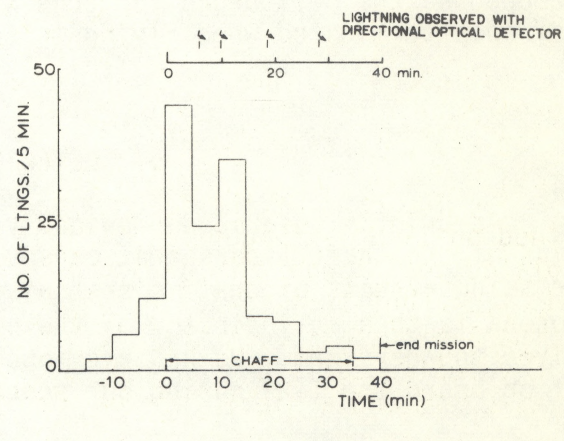


Figure 4. Lightning flashes per 5 minutes recorded on the T-29 for 19 July 1975. Also shown are the lightnings detected from within the cell into which chaff was released; these observations were made from the weather office with a directional optical detector. No data were obtained with the optical detector prior to T = 0, which is 1751 GMT, since the cell was just developing.



instrument, which has been described by Rust and Krehbiel (1977), is a microwave radiometer that operates at a frequency of 3 GHz. The receiving antenna was mounted so that it pointed about 15 degrees above the local horizon and to the side of the aircraft. We had used this configuration in our earlier research when we had two aircraft, the one that dispersed chaff and the T-29 that flew a square or rectangular pattern outside and around the entire thunderstorm. The flight "box" thus contained all the chaff that had been dispersed.

In this program at KSC, however, the T-29 was also the only seeding aircraft, and we were unable to fly the "box" pattern. The data from the corona detector were obtained as we flew through the cloud being treated. The receiving antenna beam covered a smaller portion of the cloud volume containing the chaff than it would when scanning from outside, and this made the detection of corona more difficult.

There are indications of corona from several storms, the best being 25 July. The magnitude and duration were much less than in those measured in our earlier work (Rust and Krehbiel, 1977). There are two obvious reasons for this: (1) flying through the storm rather than around or along side of it probably results in missing much of the radiation from the dispersed chaff, and (2) the relatively low fields that were measured along our random chaff-releasing tracks, especially at cloud base, undoubtedly resulted in less corona production. Both of these probably were occurring simultaneously.

6. DISCUSSION AND RECOMMENDATIONS

This brief, non-statistically configured research effort has given us some insight into how chaff might eventually be used in a full-scale field mitigation program at KSC. Several important findings have merged:

(1) It appears that there is little chance to reduce electric fields in Florida thunderstorms by releasing chaff at cloud base. This is unfortunate from an operational standpoint because of the better flying conditions generally found at cloud base. The substantial depth of cloud between the base and the high field regions of the thunderstorms in Florida is the apparent reason. This is supported by our electric field and corona measurements.

(2) Chaff may need to be released by more than one aircraft even after the optimum locations for dispersal are established because of the large size of the storm systems there.

(3) The data of the frequency of occurrence of lightning that were obtained on 19 July (Figure 4) when we dispersed chaff inside a developing, isolated cell suggest two things: (a) there might well have been a field reduction, but this cannot be ascertained definitely because of the influence of the large storm system nearby; (b) we may indeed be able to release chaff in developing cells before they are too large and hazardous for penetration by aircraft and achieve the desired reduction in the electric field.

Future research on the application of chaff seeding to the mitigation of hazardous fields in the KSC area should include these specific items;

(1) A study of the electric field and the associated charge distributions in thunderstorms to determine the optimum altitudes or temperature levels at which chaff should be released, and the earliest possible stage of storm development that can be seeded and still produce the required results.

(2) Use of a narrow-beam, ground-based radiometer to detect corona from the chaff and development of a system to "map" the areas within the storm where corona occurs and is most intense.

(3) A statistical experiment to determine the effect of chaff dispersal in thunderstorms. This experiment should include a procedure for randomly selecting the storms and the study of an adequate number of storms to yield statistically significant results.

If it is confirmed from such studies that chaff seeding is effective in the KSC area, research could proceed on applying the chaff-seeding technique to modification of thunderstorms with the goal of reducing the dangers of lightning to space vehicles during launch and return.

7. ACKNOWLEDGMENTS

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