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Review of lightning properties from electric field and TV observations

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From analysis of simultaneous electric field and TV records of 76 negative cloud-to-ground lightning flashes in Florida, various lightning properties have been determined and several new facets of lightning behavior inferred. Only 17 % of the flashes were single-stroke flashes, less than half the commonly claimed percentage (e.g., Anderson and Eriksson, 1980). The initial electric field peak (and, by inference, current peak) for the only strokes in single-stroke flashes was smaller than for first strokes in multiple-stroke flashes. Half of all flashes, single and multiple stroke, struck ground at more than one point, with the spatial separation between the channel terminations being up to many kilometers. One third of multiple-stroke flashes had at least one subsequent stroke whose distance-normalized initial electric field peak exceeded that of the first stroke in the flash. Thus such flashes are not unusual, contrary to the implication of most lightning protection and lightning test standards. Subsequent strokes of the order of 2 through 4 were more likely to create a new channel termination on ground than strokes of the order of 5 and higher. Further, leaders of lower-order subsequent strokes following previously formed and not-too-aged (100 ms or less) channels were more likely to show stepping, as opposed to continuous propagation (i.e., to be dart-stepped leaders rather than dart leaders), than were leaders of higher-order strokes. Finally, lower-order subsequent return strokes exhibited a larger initial electric field peak than did higher-order strokes. The second leader of the flash (the first subsequent leader) encounters the least favorable propagation conditions of all subsequent strokes: more than half of the second leaders either deflected from the previously formed path to ground or propagated in a stepped, as opposed to a continuous, fashion along the lowest part of that path. It is important to note that interstroke intervals preceding second strokes are similar to or shorter than those preceding higher-order strokes. These observations indicate that channel conditions for the propagation of a subsequent leader are determined not just by the immediately preceding channel heating and cooling processes but rather by the entire channel history. In particular, the status of the channel apparently depends on the number of strokes that have participated in its cumulative conditioning. The overwhelming majority of long continuing currents, those with a duration longer than 40 ms, were initiated by subsequent strokes of multiple-stroke flashes as opposed to either the first stroke in a multiple-stroke flash or the only stroke in a single-stroke flash. Strokes that initiate such long continuing currents were (1) relatively small (in terms of both return-stroke field peak and, as determined from an independent study in New Mexico, stroke charge), (2) followed relatively short interstroke intervals, and (3) showed a tendency to be preceded by a relatively large stroke. Millisecond-scale K and M electric field changes appeared different in terms of both microsecond-scale pulse content and interevent time intervals. Often no microsecond-scale K and M field pulses were detected. When they were present, such pulses were highly variable and sometimes irregular in waveshape, as opposed to the alleged characteristic K-pulse waveform described by Arnold and Pierce (1964), which has been extensively used in atmospheric radio-noise studies. There is a remarkable similarity between many lightning characteristics in Florida and in New Mexico.

1. INTRODUCTION

This survey of lightning properties is based on simultaneous single-station wideband electric field and multiple-station TV records of 76 negative cloud-to-ground lightning flashes that occurred at distances of 2 to 20 km from the field-measuring site during three convective thunderstorms near Tampa, Florida (see, for example, *Master et al.* [1984]). The TV records were an important source of information since they enabled us to identify and locate (in conjunction with thunder ranging) the lightning channels associated with individual strokes. The electric fields were recorded on analog magnetic tape and subsequently digitized at a 200-ns sampling interval (up to 10 million samples per flash) using the analog to digital (A/D) capability of a Masscomp MC5500 computer. We considered strokes to comprise a single flash if each stroke occurred within 500 ms of the previous one. A more complete data description (including many examples of recorded electric field waveforms) and more details on the results and discussion presented here can be found in the works of *Rakov and Uman* [1990 *a, b, c,* 1991], *Rakov et al.* [1990, 1991, 1992 *a, b, c*], and *Thottappillil et al.* [1990, 1992]. Part of the data for which simultaneous streak-camera records were additionally available was used by *Jordan et al.* [1992] in an analysis of subsequent-leader speed.

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2. STATISTICAL SUMMARY

Eighty three percent of the 76 flashes contained more than one stroke, with the maximum number of strokes per flash being 18. The observed percentage of single-stroke flashes (17 %) is similar to the 14 % reported for New Mexico thunderstorms by *Kitagawa et al.* [1962], but both figures are significantly lower than those from other studies (e.g., *Anderson and Eriksson* [1980] give 45 %). We attribute the disparity in part to the fact that both our study and that of *Kitagawa et al.* [1962] were superior to all others in terms of the reliability of the stroke count [*Rakov and Uman*, 1990*a*]. The average number of strokes per flash in our study was 4.6. Table 1 gives a statistical summary of the return-stroke initial electric field peak, time interval between return strokes, and leader duration as determined from the electric field records. Note the differences in electric field peak and leader duration between the first strokes in multiple-stroke flashes and the first (and the only) strokes in single-stroke flashes, as well as between subsequent strokes that create a new ground strike point and those that follow a previously formed channel. Some of the results presented in Table 1 differ from those found in previous studies based on the same tape-recorded data [*Master et al.*, 1984; *Thomson et al.*, 1984]. The present statistical data characterization is more reliable than those derived previously due to our use of more advanced data processing techniques.

3. MULTIGROUNDED LIGHTNING FLASHES

About half of the 76 flashes show spatially separate ground strike points (up to four) in the TV records. A similar fraction of multigrounded flashes was reported by *Kitagawa et al.* [1962] from photographic studies in New Mexico, an observation suggesting that our finding is not peculiar to Florida thunderstorms. In most cases, multiple ground terminations within a given flash are associated not with an individual multigrounded leader but rather with the deflection of a subsequent leader from the previously formed channel. The distances between separate channel terminations, located via TV direction finding and thunder ranging, in a given flash vary from 0.3 km to 7.3 km [*Thottappillil et al.*, 1992, Figure 2] with a geometric mean of 1.7 km. Since our TV records did not allow us to distinguish between any ground terminations separated by less than some tens of meters, due primarily to obscuration of the channel bottoms by trees, the geometric mean is likely to be an overestimate. For the same reason, our percentage (50 %) of multigrounded flashes is probably an underestimate.

4. FIRST VERSUS SUBSEQUENT STROKE INTENSITY WITHIN A FLASH

It is well known that on average the intensity (field peak or current peak) of subsequent return strokes is lower than that of the first strokes in a flash. An average peak ratio of 0.5 is considered to be typical [e.g., *Cianos and Pierce*, 1972]. However, since the majority of flashes have more than one subsequent stroke (4.6 strokes per flash for the Florida data presented here), this observation does not necessarily imply that the first stroke is always the largest in the flash. Of 46 multiple-stroke flashes for which a location of each ground termination for all the strokes was available, 15 flashes (33%) had at least one subsequent stroke whose initial electric field peak was greater than that of the first return stroke. This relatively high percentage suggests that such flashes are not unusual, contrary to the implication of most lightning protection and lightning test

TABLE 1. Statistical Summary of the Data

	Electric Field Peak at 100 km			Interstroke Interval			Leader Duration		
Characterization of Strokes	N	GM, V/m	σ log	N	GM, ms	σ log	N	GM, ms	σ log
All first strokes	76	5.9	0.22	-	-	-	70	35	0.20
First strokes in multiple-stroke flashes	63	6.2	0.23	-	-	-	58	33	0.19
First strokes in single-stroke flashes	13	4.7	0.12	-	-	-	12	46	0.23
All subsequent strokes	270	2.9	0.30	270	60	0.35	182	2.5	0.52
Subsequent strokes creating a new termination	38	4.1	0.23	38	92	0.30	28	15	0.47
Subsequent strokes in previously formed channel	232	2.7	0.30	232	56	0.35	154	1.8	0.38
Subsequent leader-return stroke sequence with negative* net electric field change	18	1.1	0.33	18	47	0.52	18	2.8	0.29

N is the sample size, GM is the geometric mean, and σ is the standard deviation of the logarithm (base 10) of the parameter.

* Usually, there is a net positive (atmospheric electricity sign convention) electric field change due to a leader-return stroke sequence lowering negative charge to ground. A net negative field change means that not all the leader charge is neutralized by the return stroke. Note the very small return-stroke electric field peak associated with the sequence exhibiting a negative net field change.

standards [e.g., *Anderson*, 1982; *Military Standard*, 1983]. Subsequent strokes with larger field peaks were observed both in the first-stroke channel (13 strokes) and in a different channel (12 strokes). Of the latter 12 strokes, 6 strokes created new channels to ground and the remaining 6 strokes followed a previously formed channel. Parameters of subsequent strokes with larger field peaks which followed the same channel as the first stroke are summarized in Table 2 (see also *Thottappillil et al.* [1992, Figure 1 and Table 1]). Note that larger subsequent strokes are associated with relatively short leader duration (and, by inference, higher leader speed) and relatively long preceding interstroke interval. Larger subsequent strokes never followed interstroke intervals shorter than 35 ms, whereas many regular subsequent strokes did [*Thottappillil et al.*, 1992, Figure 1*c*].

5. LIGHTNING PROPERTIES VERSUS STROKE ORDER

A number of lightning properties derived from simultaneous electric field and TV records appear dependent on stroke order. Several of our findings indicate that there is something different about the channel status for the first few subsequent strokes and for strokes occurring after four or more strokes of the flash have bridged the cloud source and ground. In the first group, the second stroke of the flash (the first subsequent stroke) appears as most distinctive in this regard. Several observed lightning properties are presented as a function of stroke order in Table 3. We briefly discuss these below.

5.1. Creating a New Channel Termination on Ground

The percentage of subsequent leaders that create a path to ground different from that of the previous stroke path decreases rapidly with stroke order: 37 % of all second leaders, 27 % of all third leaders, 2 % of all fourth leaders, and none of the leaders of the order of 5 and higher [*Rakov and Uman*, 1990*b*, Figure 4]. Interestingly, if only those third leaders which followed the formation of a new second-stroke path to ground (19 total) are considered, the percentage of the new terminations is 37 %, the same as for second leaders, all of which are preceded by the formation of a new channel, the first-stroke channel. We interpret these results as indicating that the first stroke (or even a sequence of the first two strokes) of the flash often does not create a properly conditioned channel capable of supporting the propagation of the following leader all the way to ground. An unalterable path to ground in a given flash is apparently established only after at least four consecutive strokes have participated in channel conditioning. Note that the behavior described above cannot be explained in terms of relatively long preceding interstroke intervals (and hence more aged channels) for strokes of the order of 2 through 4. In fact, the fraction of interstroke intervals lasting longer than 100 ms and not containing long continuing current for strokes from 2 to 4 is about the same as for the higher-order strokes. Further, the geometric mean preceding interstroke interval for second strokes is similar to that for strokes of the order of 5 and higher (see Table 3).

TABLE 2. Geometric Mean Values for Various Parameters of Larger Subsequent Strokes in the Same Channel as the First Stroke Versus Those for All Subsequent Strokes in the First-Stroke Channel

Parameter	Larger Strokes	All Strokes
Return-stroke field peak (at 100 km), V/m	7.7 (13)	2.6 (176)
Return-stroke current peak*, kA	- 27	- 8.1
Preceding interstroke interval, ms	98 (13)	53 (176)
Leader duration, ms	0.55 (8)	1.8 (117)
Ratio of subsequent to first stroke field peak	1.2 (13)	0.39 (176)

The numbers in the parentheses are the sample sizes.

* Inferred from formula $I_p = 1.5 - 3.7{*}E_p$ where E_p is return-stroke initial electric field peak normalized to 100 km taken as positive and in V/m, and I_p is return-stroke current peak, negative, and in kA [Rakov et al., 1992*b*].

TABLE 3. Properties of Subsequent Leaders and Return Strokes Versus Stroke Order

Feature	Stroke Order		
	2	2 - 4	5 - 18
Probability of creating a new termination,%	37 (63)	25 (155)	0 (115)
Occurrence of leader stepping in previously formed channel, %	36 (36)	21 (86)	4.5 (88)
Occurrence of apparently inactive final portion in leader field waveform, %	29 (63)	24 (155)	6.1 (115)
Occurrence of leader-return stroke sequence with negative net electric field change, %	0 (63)	1.3 (155)	14 (115)
Geometric mean return-stroke field peak, V/m	3.4 (63)	3.3 (155)	2.3 (115)
Geometric mean duration of leader in previously formed channel, ms	1.2 (24)	1.5 (71)	2.2 (83)
Geometric mean preceding inter-stroke interval, ms	56 (63)	66 (155)	54 (115)

The numbers in the parentheses are the sample sizes.

5.2. Leader Propagation Mode

When a subsequent leader follows a previously formed channel after a not-unduly-long interstroke interval of 100 ms or less, one might anticipate that the leader will propagate continuously. For the second leader of the flash this is often not the case: 36 % exhibited electric field pulses characteristic of dart-stepped leaders. This percentage is more than 5 times greater than for strokes of higher order taken together [*Rakov and Uman*, 1990*b*, Figure 5]. We interpret this observation as indicating that the first-stroke channel is often insufficiently conditioned to support a continuously moving dart leader. The higher-order strokes in previously formed channels are more likely to be initiated by pure dart leaders than are second strokes, suggesting that the channel is more conducive to continuous leader propagation after it has been repeatedly conditioned by several strokes. This interpretation is similar to that given in section 5.1 relative to the statistics on new channel terminations.

5.3. Magnitude of the Subsequent Return-Stroke Electric Field Peak

The return-stroke initial electric field peak normalized to 100 km is greater for strokes of the order of 2 through 4 (even if strokes creating a new ground termination are excluded) than for higher order strokes [*Rakov et al.*, 1991, Figure 6]. A similar behavior is exhibited by the charge lowered by subsequent strokes [*Brook et al.*, 1962]. Both results can be interpreted, similar to the results presented in sections 5.1 and 5.2, in terms of the existence of less favorable channel conditions for the lower-order strokes than for the higher-order strokes (the better the conditions the less charge is required to drive the leader through the channel to ground [*Rakov and Uman*, 1990*b*]). Interestingly, abnormal electric field changes from subsequent leader-return stroke sequences [e.g., *Rakov et al.*, 1990, Figure 5], those that are net negative (atmospheric electricity sign convention), show a tendency to have a small return-stroke field peak (see Table 1) and to occur late in a flash (see Table 3). Note that subsequent return-stroke current peaks are correlated with distance-normalized field peaks [*Rakov et al.*, 1992*b*]. As a result of this correlation, current peaks can be expected to behave in a similar fashion to the field peaks.

5.4. Leader Field Waveform Characteristics

Some subsequent leaders exhibit an apparent inactive final portion characterized by a pronounced flattening in their field waveforms [see *Rakov and Uman*, 1990*c*, Figures 4, 5, and 8*c*]. The fraction of strokes showing this behavior, hypothesized to be related to some kind of in situ effective neutralization of the leader charge [*Rakov and Uman*, 1990*c*], appears highly dependent on stroke order: 24 % for strokes of the order of 2 through 4, while only about 6 % for higher-order strokes.

The leader duration for strokes following a previously formed channel increases with stroke order [*Rakov and Uman*, 1990*c*, Figure 10]. If leader speed is not influenced by stroke order, this tendency implies a progressive increase in the channel length with stroke order. Further, the leader to return-stroke field change ratio tended to be more negative as the stroke order increased, suggesting that the charge sources for successive strokes were, on average, progressively farther from both the observer and the ground strike point [*Rakov et al*, 1990].

6. LONG CONTINUING CURRENTS

The overwhelming majority of long continuing currents (those longer than 40 ms) are initiated by subsequent strokes of multiple-stroke flashes as opposed to either the first stroke in a multiple-stroke flash or the only stroke in a single-stroke flash. There appears to be a pattern in initiating long continuing currents [*Shindo and Uman*, 1989; *Rakov and Uman*, 1990*a*; *Rakov et al.*, 1991]. First, strokes initiating long continuing current tend to have lower initial electric field peak than regular strokes, the latter defined as neither initiating long continuing current, nor preceding those doing so, nor following long continuing current interval. Secondly, strokes preceding those initiating long continuing current are more likely to have a relatively large field peak than regular strokes. The data of *Brook et al.* [1962] on charge lowered by individual strokes show the same tendency, that is, long continuing current is usually initiated by a smaller stroke following a larger stroke. Speculations regarding why larger strokes often appear to be incapable of initiating long continuing currents, related to the deposition of positive charge in the cloud by return strokes, are given by *Rakov and Uman* [1990*a*]. Finally, strokes initiating long continuing current are usually preceded by relatively short interstroke intervals. All these features (besides potentially providing some insights into the physics of the continuing current process) can be used for the detection of the relative occurrence of hazardous long continuing currents in different geographical locations, seasons, types of storms, or stages of storm life cycle with commercially available lightning-locating systems [e.g., *Rakov*, 1990].

7. K AND M ELECTRIC FIELD CHANGES

Processes that produce K changes in cloud-to-ground lightning fields occur during interstroke intervals or after the final stroke when the channel to ground is not luminous. Processes which produce M changes occur in the latter stages of return strokes or during continuing currents when the channel to ground is still luminous. Both K and M processes are relatively minor from the point of view of lightning effects on man-made objects (compared to return strokes and continuing currents), but they are nevertheless important for an understanding of the spatial and temporal structure of the cloud charge and its relation to the lightning. K and M processes were claimed to be similar by *Kitagawa et al.* [1962] based on their reported similarity of the interevent interval distributions. Our data [*Thottappillil et al.*, 1990] on interval distributions do not support this assertion. We also found that K and M processes are dissimilar in terms of their microsecond-scale electric field pulse activity. In particular, M processes exhibit pulses more frequently than K processes and the M-process pulses tend to occur at the beginning of the M change whereas the K-process pulses are often delayed with respect to the beginning of the K change [*Rakov et al.*, 1992*a*]. Additionally, the microsecond-scale field pulses in our K and M changes are often undetectable and, when present, are highly variable and sometimes irregular in waveshape, as opposed to the characteristic K-pulse waveform described by *Arnold and Pierce* [1964], which has been extensively used in atmospheric radio-noise studies.

8. CONCLUDING REMARKS

The purpose of this survey has been to summarize the several analyses of lightning properties derivable from simultaneous electric field and TV recordings obtained in 1979 near Tampa, Florida, by the University of Florida lightning research group. Generally speaking, the results of those analyses can be viewed as providing additional pieces to the puzzle of the physics of the lightning discharge. Some findings, in particular those regarding the occurrence of single-stroke flashes, multiple ground strike points, and the relative stroke intensity within a flash, may have important implications for lightning protection and lightning test standards. The pattern of field peaks and interstroke intervals associated with long continuing currents could be used for the detection, with presently operating lightning locating systems, of lightning flashes containing those currents. The results on the microsecond-scale K field pulses may alter the theoretical K-change frequency spectrum commonly found in atmospheric radio-noise studies. Our newly advanced hypothesis regarding cumulative conditioning of lightning channel by consecutive strokes and our interpretation, although speculative, of the observed relation between field peak and initiation of long continuing current provide some clues to the physics of the lightning processes.

In view of the dissimilarities between the occurrence of single-stroke flashes and multigrounded flashes reported here and elsewhere [e.g., *Anderson and Eriksson*, 1980], one might question whether the present results obtained in Florida are applicable to other geographical locations. In Table 4 we compare our findings for Florida with those obtained by *Kitagawa et al.* [1962] and *Brook et al.* [1962] for New Mexico. It is important to note that the latter observations are based on simultaneous electric field and photographic records which, similar to our data, provide a very reliable stroke count. Given the differences in measurement techniques and, additionally, the use of different quantities to express stroke intensity, the overall results from Florida and New Mexico appear remarkably similar. This similarity leads us to postulate that lightning features presented here are applicable to many geographical locations, not only to Florida. At any rate, before suspecting that any regional or meteorological peculiarities are influencing lightning properties, one should make certain that measuring and data processing techniques used in different locations possess similar capabilities so as to allow a meaningful comparison of the different measurements. For example, such features as the fraction of single-stroke flashes or the average number of strokes per flash are extremely sensitive to the reliability of the stroke identification process. As a result, those features obtained using triggered measuring systems designed to record individual strokes [e.g., *Namasivayam et al.*, 1990, Figure 2; *Casper and Bent*, 1992, Figure 6] are necessarily in error due to the missing of small strokes that fail to exceed the trigger threshold level, the degree of error depending on the trigger threshold setting in conjunction with the characteristics of the source, storm range, and propagation effects, and therefore cannot be as reliable as the data derived from appropriately processed continuous recordings.

TABLE 4. Comparison of Various Lightning Properties in Florida and New Mexico

Feature	Florida	New Mexico
Percentage of multigrounded flashes, %	50 (76)	49* (72)
Percentage of single-stroke flashes, %	17 (76)	14 (193)
Percentage of single-stroke flashes containing long continuing current, %	7.7 (13)	7.4 (27)
Percentage of multiple-stroke flashes containing long continuing current, %	43 (63)	52 (166)
Average number of strokes per multiple-stroke flash without long continuing current	4.3 (36)	7.2 (36)
Average number of strokes per multiple-stroke flash with long continuing current	6.6 (27)	7.2 (36)
Intensity of strokes initiating long continuing current and strokes preceding those doing so relative to the intensity of regular strokes, respectively	0.59 : 1.5	0.52 : 1.6
Ratio of intensity of first strokes in multiple-stroke flashes to that of the only strokes in single-stroke flashes	1.3	1.6†
Ratio of intensity of strokes 2 through 4 to that of strokes of the order of 5 and higher	1.4	2.1

The numbers in parentheses are sample sizes. "Intensity" of stroke indicates geometric mean return stroke initial electric field peak for Florida and geometric mean stroke charge for New Mexico.

* Multiple-stroke flashes only.

† The ratio of the means, as opposed to geometric means, is given in this case.

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