ON THE FINE STRUCTURE OF ATMOSPHERICS FROM NEAR ORIGINS

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Synopsis—In the previous paper the authors classified the atmospheric wave-forms from near origins into three fundamental types, *i.e.*, main discharge type, leader discharge type and partial discharge type. It has been studied further in this paper, the fine structure of the leader discharge type wave-forms from cumulo-nimbus which has grown up to a stage just before a thunder-cloud, the wave-forms from cloud to earth discharges, and the main discharge type wave-forms in calm days.

Widths of pulses of differential type wave-form and their intervals of occurrence, of which a leader discharge type wave-train is constructed, are found to have their most frequent values of about 60 micro-seconds and 250-350 micro-seconds respectively. A statistical investigation of these pulses produced by intra-cloud discharge in cumulo-nimbus shows that the stepped leader like character of them corresponds unlikely to the stepped leader stroke as in the case of the cloud to earth discharge, but represents presumably the small local separate dart leader like sub-discharges which are simultaneously superposed upon the violent main cloud discharge of stepped leader character.

The analysis of clear pulsive wave trains, which correspond to the cloud to earth discharge that occurred within several hundred metres from the observation station, shows the similar values of pulse interval and pulse width to those of intra-cloud discharge in the earlier stage. The interval of pulses reduces to 30-60 micro-seconds in the later stage, but the pulse width on the other hand does not reduce so evidently as pulse interval. Although the authors assume that these recorded wave trains are produced from the first leader stroke of this lightning, it is not evident at present the reason why the intervals are larger and the pulse width has the measurable value of more than several ten micro-seconds in the earlier stage.

The simultaneous observation of lightning and corresponding discharge wave-form shows that the first large pulse of the main discharge type wave-form, which corresponds to cloud to earth discharge, should be interpreted as to be emitted from the main part of return stroke of the corresponding cloud to earth lightning.

Comparison between the wave-forms of main discharge type in calm days and those obtained during thunder-storms, which correspond perhaps both to cloud to earth discharge and to intra-cloud discharge of special type, indicates that the main discharge type wave-form in calm days does not always interpreted as to be emitted from the return stroke of a cloud to earth lightning, but some times may be interpreted as to be radiated from a special type discharge in the cloud.

I. Introduction

It is an interesting problem to study the wave-forms of atmospherics from near origins from the stand-point of electro-magnetic wave radiation mechanism from lightning discharge and to investigate the possible elementary wave forms as a whole which are radiated from an advancing discharge streamer of various kinds, and to establish the fundamental wave forms at the atmospheric origins. Norinder[1] and Lutkin[2] already culculated the radiation field from lightning current variation and static field change observed during thunder-storms respectively and Schonland[3] assumed the wave-form at origin to be a single pulse from the investigation of distant atmospheirc wave-forms at night but their discussions concerned chiefly on the wave-forms from the main stroke of a lightning. Malan[4] recently pointed out that radiation field become already predominant when the lighting occurs at few ten kilometers distant from the observation station, and Schonland, Hodges[5] computed that the stepped leader streamer should produce a static field change of a step like form, and that the atmospheric wave forms at moderate distance should represent the radiation field, the amplitude of which corresponds accordingly to the rate of change in the streamer current in lightning channel. In these connections it is attempted in this paper the interpretation of wave-forms from near origins from the discharge mechanism of lightning through a statistical treatment of their fine structure characteristics.

II. Wave-Form from Intra-Cloud Discharge in Cumulo-Nimbus

When the fine detailes of individual wave-forms are to be taken into accunt, there are much varieties in leader discharge type wave-forms which correspond to intra-cloud discharges in cumulo-nimbus sufficiently developed to a state just before a thunder-cloud, there remains, however, some common clear characteristics throughout them. Fig. 1. illustrates the typical examples of wave-form from intra-cloud discharge, and represents the clear repetition of differential type pulses of radiation field character, the duration of which amounts often to more than 6 milli-seconds. The percentage distributions of their intervals having large, medium and small amplitudes are represented by the curves (1), (2) and (3) in Fig. 2. respectively, the numerical values of which are tabulated in Table 1. The most frequent values of them are about 250–350, 60–70, and 20–30 micro-seconds, and the distribution ranges of them are 100–1,500, 30–300, and 5–100 micro-seconds respectively. Accoding to the observation made by Schonland[6] air and cloud discharges are associated with no return stroke of lightning and the individual step leader streamer radiates each the pulsive radiation field due to the small but rapid static field change produced by each step leader streamer to advance in a micro-second or so through the channel length of several ten metres previously tapped by the pilot streamer. On the other hand Malan[4] pointed out that the radiation field becomes already observable at about several ten kilometers from the lightning channel. In our case the discharges were taken place in cumulo-nimbus within the view field, which floated probably at about 30 kilometers from the observation station, so that it should be plausible to consider that the observed individual differential pulse comes from each step leader streamer in the intra-cloud lightning channel. There should not have occured so many repetitions of differential pulses, if the concerning intra-cloud discharge had been consisted of dart streamers of multiple type. According to the result observed by Schonland[7] the step intervals must range 30-90 micro-secs. and the value that frequently occurs is about 50 micro-secs. This corresponds in our case to the curve (3) and therefore the curves (1) and (2) must represent that the fluctuations in the rate of stepped leader current change are occurring at intervals of several steps in the leader channel. The widths of large amplitude pulses, however, have sufficiently large values to be evaluated numerically

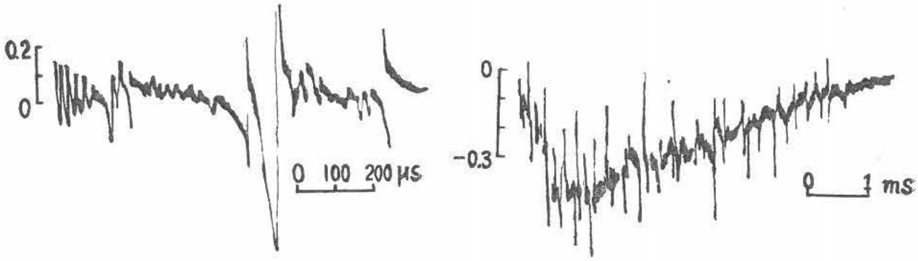


FIG. 1. Typical atmospheric wave-form from intra-cloud discharge.

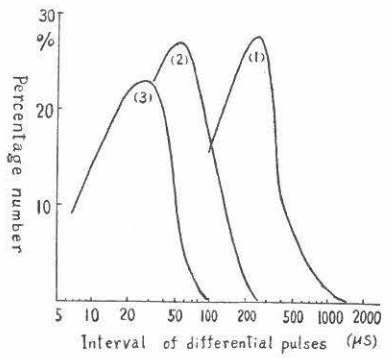


FIG. 2. Percentage number distribution of individual differential pulse intervals in the wave-form from intra-cloud discharge.

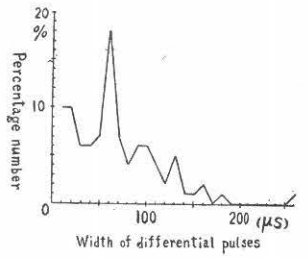


FIG. 3. Percentage number distribution of large amplitude differential pulse widths from intra-cloud discharge.

TABLE 1. Pulse Interval in the Wave-Form from Intra-Cloud Discharge

Large amplitude pulse		Medium amplitude pulse		Small amplitude pulse	
Pulse interval in μs	Percentage number	Pulse interval in μs	Percentage number	Pulse interval in μs	Percentage number
0- 100	16.3	0- 45	24.1	0- 10	10.6
100- 200	27.0	45- 70	26.4	10- 20	21.0
200- 300	22.4	70- 95	19.5	20- 30	23.0
300- 400	10.7	95-120	11.5	30- 40	20.6
400- 500	7.6	120-145	6.9	40- 50	13.3
500- 600	3.8	145-170	9.2	50- 60	5.8
600- 700	3.8	170-195	2.3	60- 70	3.0
700- 800	3.1			70- 80	1.7
800- 900	1.7			80- 90	0.6
900-1,000	1.6			90-100	0.2
1,000-1,100	1.0				
1,100-1,200	0.2				
1,200-1,300	0.0				
1,300-1,400	0.2				
1,400-1,500	0.2				
1,500-1,600	0.0				
1,600-1,700	0.2				
1,700-1,800	0.0				
1,800-1,900	0.2				
1,900-2,000	0.0				

on the oscillographic record. Table 2 and Fig. 3 represent the percentage number distribution of them. The curve shows a clear maximum at 60 micro-seconds and ranges from 5-200 micro-seconds. When the clear peak at 60 micro-seconds is brought out of our consideration, the pulses of smaller widths are seen to occur more frequently than those of larger widths. This may come partly from the insufficient over-all gain of the instrument used in the observation, which results the underestimation of the individual pulse width, and partly from the fact that the step leaders of small duration occur more frequently than those of large duration.

TABLE 2. Percentage Number of Differential Pulse Width from Intra-Cloud Discharge

Differential pulse width in micro-second	Percentage number	Differential pulse width in micro-second	Percentage number
0- 10	9.0	100-110	4.0
10- 20	9.0	110-120	2.0
20- 30	6.0	120-130	5.0
30- 40	6.0	130-140	1.0
40- 50	7.0	140-150	1.0
50- 60	18.0	150-160	2.0
60- 70	7.0	160-170	0.0
70- 80	4.0	170-180	1.0
80- 90	6.0	260-270	1.0
90-100	6.0		

If each of the step leader produces a step like electro-static field change as Schonland proposes,[5] the radiation field must have a differential pulse form, and the width of it must be equal to the whole duration of the sudden static field change of step like character. Therefore the widths of the differential pulses are the indication of the time necessary for the advance of rapid leader streamer through a distance in the lightning channel previously tapped by preceding pilot streamer. Assuming the leader streamer velocity of 5×10^9 cm/sec. the streamer must advance 3 kilometers in 60 micro-seconds, therefore the step length of 3 kilometers must be concluded, but this conclusion contradicts to the result obtained by the Boys camera investigation.[7] On the other hand Meek and Loeb[8] considered that each step streamer starts every time from the cloud end of the lightning channel. According to these ideas the distance which one step streamer must travels down along the channel must increases from one step to another, therefore the pulse widths must increase from one to another with the order of them in a wave train of differential pulses forming a wave form of atmospheric. Table 3 and Fig. 4 show how varies the large amplitude pulse width with the order of pulses in a pulsive wave train forming a wave of atmospheric. The values of pulse widths are refered to the first one in a wave train and the data represent the mean value of ten wave forms. As the interval between the first pulse and the last pulse corresponding to Fig. 4 is roughly 3 milli-seconds, the channel length increase in this interval must be 1.1 km assuming the pilot leader velocity of 4×10^7 cm/sec. Therefore step streamer duration or pulse width must increase by the amount of about 20 micro-seconds from the first pulse to the last pulse in the same wave, if we take the velocity of stepped leader streamer to be 5×10^9 cm/sec. and accept the idea of stepped leader process proposed by Meek and

TABLE 3. Distribution of Pulse Width of Large Amplitude Pulses in a Wave Train

Order of individual pulse	Relative pulse width in a pulsive wave train	Order of individual pule	Relative pulse width in a pulsive wave train
1	1.0	6	0.84
2	0.67	7	0.62
3	0.83	8	0.48
4	0.80	9	0.62
5	0.65	10	0.68

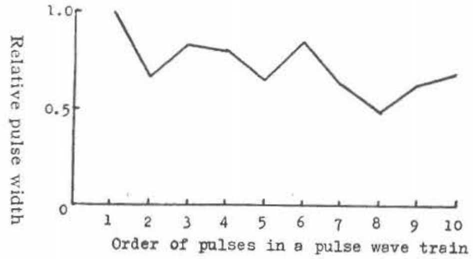


FIG. 4. Distribution of differential pulse widths of large amplitude pulses in a wave train.

Loeb. On the other hand it will be possible that the pulse width can be measured apparently as if it were reduced, when the over-all gain of the instrument is insufficient to record the detailes of whole pulses in a wave train with sufficient magnification, that is, when the recorded pulse amplitude reduces with the order of the pulses. As there is a clear reduction of pulse amplitude with the order of the pulses in the present case, of which point will be discussed in the next section, the apparent pulse width may be measured as if to reduce from pulse to pulse, and the rough estimation of the magnitude of this reduction indicates this to be at most about 20–30 micro-seconds. Therefore these two effects roughly compensate each other in the worst case, and the reduction of the pulse width will not present itself in a clear manner. But Fig. 4 shows that the pulse width clearly reduces with the order of the pulses in a wave train, even if it is considered the accuracy of the measurement on oscillogram, *i.e.*, 10 micro-seconds. This point also contradicts to Meek's idea, hence the conclusion may be made that the differential pulses of large amplitude, which is superposed on small amplitude differential wave train, do not at least produced from the individual step streamer processes but from some other multiple dart leader like discharge processes occurring simultaneously in connection with the step leader like discharge under consideration, which composes the main part of a intra-cloud discharge.

The amplitude distribution of these large amplitude differential pulses in a pulsive wave train is reproduced in Fig. 5 and Table 4. Each pulse amplitude in the train is referred also to that at the top and the data obtained from ten typical wave-forms just mentioned. The amplitude of differential pulses reduces generally with the turn of the pulses in a wave train, which may indicate that the leader streamer reduces its violence with the repetition of the discharge in multiple or almost simultaneously occurring several dart leader like discharges as in the case of components in a return stroke. The reduction in amplitude of small amplitude pulses are also observed but the discussion will be postpond according to the lack of sufficient data for the discussion.

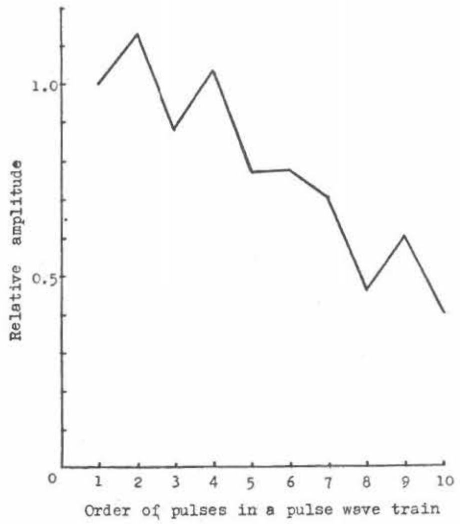


FIG. 5. Relative pulse amplitude distribution of large amplitude pulses in a wave train.

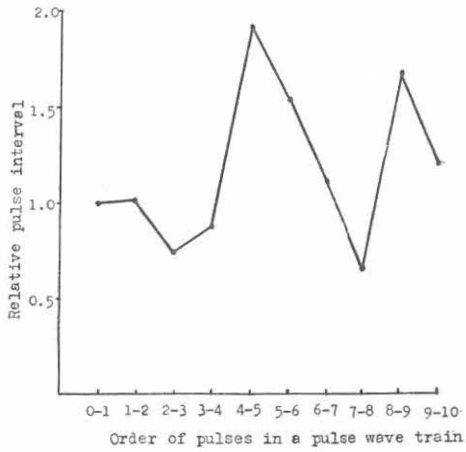


FIG. 6. Relative pulse interval distribution of large amplitude pulses in a wave train.

TABLE 4. Distribution of Relative Pulse Amplitude of Large Pulses in a Wave Train

Order of individual pulse	Relative amplitude of individual pulse in a pulsive wave train	Order of individual pulse	Relative amplitude of individual pulse in a pulsive wave train
1	1.0	6	0.77
2	1.13	7	0.70
3	0.88	8	0.46
4	1.03	9	0.60
5	0.77	10	0.40

TABLE 5. Distribution of Relative Pulse Interval of Large Amplitude Pulses in a Wave Train

Order of pulses in a pulsive wave train	Relative pulse interval in a pulsive wave train	Order of pulses in a pulsive wave train	Relative pulse interval in a pulsive wave train
0-1	1.0	5- 6	1.56
1-2	1.02	6- 7	1.14
2-3	0.75	7- 8	0.68
3-4	0.89	8- 9	1.60
4-5	1.94	9-10	1.24

The large amplitude pulse interval distribution in a wave train reproduced in Fig. 6 and Table 5, which is obtained from ten typical wave forms above mentioned, shows much greater randomness than in the case of pulse width in the same wave trains, which indicates that the dart leader like discharges in the cloud radiating large amplitude differential pulses are occuring almost at random as in the case of multiple return stroke. In addition to this there is no evident relation between pulse interval and immediately following pulse amplitude. Fig. 7 and Table 6 show few examples of the relation between the large amplitude pulse interval and the pulse amplitude which followed immediately the former. The numbers attached to the curve in the figure represent in order of individual differential pulses of large amplitude in the same wave trains. It is clear from these curves that the amplitude of differential pulse which occurs immediately after a longer interval of pause is not always larger than that which followed immediately after a shorter pulse interval. This will be explained by the fact that it is not the charge itself which concerns the radiation of differential pulses in a wave train, but it is the rate of change in electric current that must be taken into account. It is difficult to estimate accurately the total duration of the pulse wave train owing to the insufficient length of scanning duration of our oscillograph, but the lower limit of it including small amplitude pulses can be obtained from the data observed. Fig. 8

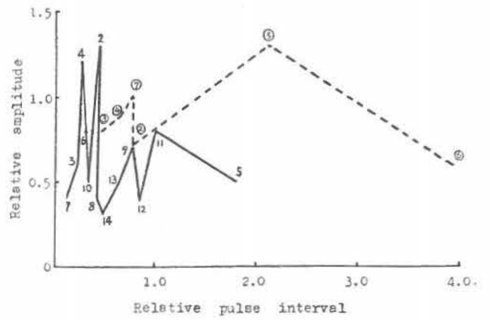


FIG. 7. Relation between the large amplitude pulse interval and the pulse amplitude which followed immediately the former, represented by relative values.

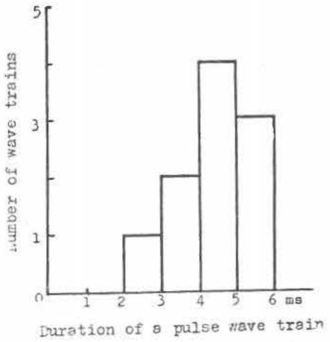


FIG. 8. Distribution of total duration of pulse wave train including small amplitude pulses.

TABLE 6. Relation between Relative Pulse Amplitude and Relative Pulse Interval of Large Amplitude Pulses in a Wave Train

Wave number	Order of differential pulse in a wave train	Relative amplitude of differential pulse*	Relative interval just preceding the differential pulse*
Wave I	2	1.3	0.45
	3	0.6	0.23
	4	1.1	0.26
	5	0.5	1.80
	6	0.8	0.33
	7	0.4	0.12
	8	0.4	0.43
	9	0.7	0.80
	10	0.5	0.35
	11	0.8	1.00
	12	0.4	0.85
	13	0.5	0.65
Wave II	2	0.7	0.70
	3	0.8	0.45
	4	0.9	0 65
	5	1.3	2.10
	6	0.6	3.95
	7	1.0	0.80

* References are made to the first interval and the first pulse.

shows the result obtained. It will be seen from the distribution that the duration of the pulse wave train continues generally more than 6 milli-seconds if we consider the delay of the starting in recording instrument. Assuming the total duration of the pulsive wave train including small amplitude pulses to be 6-10 milli-seconds and the pilot velocity to be 4×10^7 cm/sec.,[5] we can estimate the frequent values of the channel length of intra-cloud discharge to be 2.4-4 km. Considering the large amplitude pulse as to correspond to dart leader streamer, we can see that the dart leader streamer having the velocity 2×10^8 cm/sec. continues to advance for about 60 micro-seconds, hence the dart leader channel length should be 120 meters, but if the dart streamers are the multiple type the ion density reduction in the channel in dart streamer intervals of 250-350 micro-seconds must be must less than that in the stroke intervals of a multiple lightning, accordingly in this case the dart leader channel length increase to a value of about 600 meters.

In the interior of the cumulo-nimbus in summer developed to a certain stage the charge separation of the electricity must be considered to take place in high degree. For example the measurement of the charge quantity of electricity in rain water droplets in shower shows that the ion density that they contain must be more than 10^8 ions/cc. It is not unreasonable to suppose that the ion-density in the interior of the summer cumulo-nimbus often reaches to a threshold value which is neccessary to start a dart leader streamer, *i.e.*, 10^7 ions/cc. Therefore the discharge of dart leader character can take place with out any preceding step-character streamer in the interior of the cloud, which may be confirmed through the photographic observation of air discharges made by Schonland.[7] Moreover we know a photograph which represents more than fourteen air lightning discharge channels spread out to all directions from a small isolated cloud mass. It will be reasonable to consider from above discussions that the observed wave trains of differential pulses should come from the cloud discharge, which constructed from a main channel of stepped leader and several other short simultaneous sub-channels of dart streamers. In sufficiently developed cumulo-nimbus small ignition discharges will occur in some transient local charge centres as Loeb pointed out[9] and some of them will have a chance to grow up to a stepped leader streamer if the field is strong enough to produce the stepped leader advance but the ion-density is insufficient for the development of the dart leader streamer between the charge centres in large scale. The other small ignition streamers will not have the chance to grow up to stepped leaders in large scale and they may end as small dart streamers in the neibourhood of the initial transient local charge centres. The wave-forms from these sort of discharges therefore should be composed from stepped leader radiation pulses of small amplitude superimposed by the multiple type dart leader radiation pulses of large amplitude.

III. Wave-Form of Discharge to Ground

A characteristic wave-form which corresponded clearly to lightning to ground that occurred at distance of several hundred metres from our observation station was obtained during the thunder-storm observation in summer 1952, which is reproduced in Fig. 9 *A*. As the over-all gain of instrument was controlled at that time to a value suitable to record the cloud-to-earth lightning wave-form at several ten kilo-meters distant place, the wave-form corresponding to return stroke of this almost

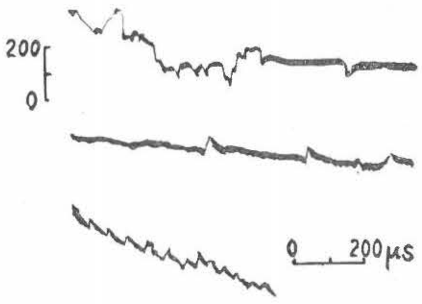


FIG. 9 *A*. Leader wave-form obtained from over-head lightning to ground.

over-head lightning might be missed out of the scale. The wave-form represented by three partial wave trains have small but clear differintial pulsive waves being superposed on the slow negative change of stiatic field character, which will be seen to be in accord with the static leader field change of over-head lightning to ground.[10] Hence it may be surmised that the recorded wave is produced from the stepped leader to the first stroke of this discharge to ground, even if it has multiple structure, because it is only the leader to first stroke that has the stepped character. It may be also presumed from the character of slow static field change that the three pulsive wave trains I, II, and III in Fig. 9 *A*. represent the discretely successive portions of a stepped leader respectively. The first half of the wave train I represents a random irresular character of differential pulses, but the second half of it and the wave trains II, III represent a clear repetition of the differential pulses which may be assumed to correspond to the stepped leader streamer of the lightning to ground in the present discussion.

Table 7 represents the values of individual pulse intervals and those of individual pulse widths measured from the wave trains in Fig. 9 *A*. The magnitudes of the static field change at each pulse and in each pulse interval are tabulated in Table 8. From the idea proposed by Schonland[5] it will be concluded that the stepped leader wave-from of a over head lightning to ground must have the wave-

TABLE 7. Pulse Intervals, Widths and Total Durations Obtained from Fig. 9 *A*

Wave number	Pulse interval in micro-secs.	Pulse width in micro-secs.	Total duration of observed wave train in micro-secs.
I	240 210	5-20* 20-34*	440
II	larger than 380 285 230	30-48* 15-24* 15-32*	910
III	50 50 60 55 62 56 32 30 35 35	less than 5 〃 10 12 13 8 12 hard to be maesured	350

* The true values of these pulses will be lie between these two values.
The accuracy of the time scale measurement on oscillograph record is estimated to lie roughly between 10 micro-seconds.

TABLE 8. Field Changes at and between Pulses obtained from Fig. 9. *A*.

Wave number	Relative static field jump at each pulse	Relative static field change in the interval of pulses	Relative rate of static field change per micro-secs.	
			At each pulse	In the interval of pulses
I	less than 10	20	0.3	0.08
II	less than 10 ″ 5	45 50	0.2 0.2 0.3	0.10 0.17

The acurracy of relative field strength measurement is about 10.

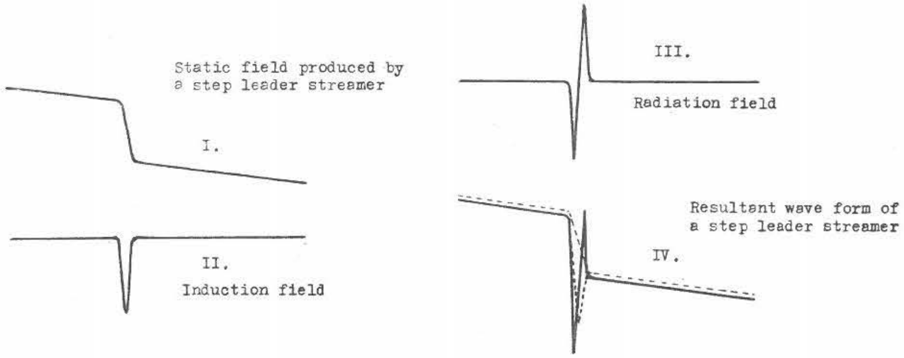


FIG. 9 *B*. Schematical representation of electric-field radiated from a stepped leader process.

form represented schematically in Fig. 9 *B*, in which the wave-form I represents the small electro-static field change of step character produced by a stepped leader streamer to the first stroke and the gradual decrease of the static field between steps indicates the slow field change produced by the continuously downward moving pilot-streamer. The wave II in the same figure indicates the induction field change corresponding to the static field change in step form due to the stepped leader and the wave III represents the radiation field corresponding to the induction field change. As these three electric-field changes present themselves simultaneously corresponding to the stepped leader streamer, the resultant waveform of the leader to the first stroke of a over-head lightning which may be observed will be represented by a composed wave train of these three fundamental wave forms, which is indicated by the wave IV in the same figure. It will be seen from Fig. 9 *A*. that each typical wave train of pulses has the clearly analogous feature as a whole to the presumed ideal case represented by the wave IV in Fig. 9 *B*. The pulse intervals represented by the first two wave trains in Fig. 9 *A*. are 210–385 micro-seconds and that of the third wave train is 30–62 micro-seconds. The values of former intervals will be too large to be considered to represent the step interval of the first leader stroke of a lightning to ground, but they will be identified rather with the values of the pulse intervals in the intra-cloud discharge wave-forms discussed in the preceding paragraph, on which the slow static field change is often superposed every time when the discharge takes place within the distance of 20–30 kilometers. The pulse width of these large interval pulses of wave trains I. II. are measured to be roughly 5–50 micro-seconds as tabulated in Table 7, hence it is also difficult to distinguish the difference between the pulse widths in the wave train corresponding to intra-cloud discharge and those in the wave train corresponding to the lightning to ground under discussion, even if we consider the accuracy of measurement on the oscillographic record. At any rate the mean pulse width of roughly 25 micro-seconds is difficult to be interpreted by the model proposed by Schonland,[5] if we assume the pulses in the atmospheric wave to correspond to the stepped leader streamers in a lightning discharge to ground. On the other hand it will be concluded from Meek's theory of lightning discharge that the leader streamer travels about 1.2 km, *i.e.*, the leader field change is recorded by our instrument at the moment when the leader channel extended roughly 1 km. Moreover such long interval as 210–285 micro-seconds between the differential pulses, which must correspond to the step interval according to the above interpretation, is implausible from the investigation by Boys' camera method.[7] Therefore we may presume that first two wave trains in Fig. 9 *A*, represent the wave-form corresponding to intra-cloud discharges preceding to the lightning to ground, which has the character discussed in the preceding paragraph, if we take account of the point that the slow static field change is often observed to be superposed on the wave-form between the large pulses also in the case of intra-cloud discharge. The interpretation of this slow static field change seems to be difficult to be given at the present stage of investigation.

The pulse interval in the third wave train distributes from 30 to 60 micro-seconds, which is reasonably interpreted as to correspond to the step interval of stepped leader stroke, but the pulse width of individual pulses that distributes from 5 to 13 micro-seconds is roughly comparable with the accuracy of the measurement. Therefore it is difficult to discuss from the above few data the meaning of width of pulsive field change. However, it might be not unreasonable to consider that the radiation field pulse corresponding to step leader streamer has really much larger duration than the value which can be estimated by Schonland's model, in which the step leader streamer duration is estimated to be of the order of 1 micro-second from the Boys' camera record.[5] Moreover the third wave train III of Fig. 9 *A*. represents the individual pulses to be superposed on a slow negative field change of static character, it is, however, also difficult to measure the magnitude of it between the pulses as in the case of the first two wave trains I, II, on account of the contraction of pulse interval.

The jump of static field strength at each pulse is also too small to be measured with sufficient accuracy, nevertheless it is evident that the static field change in the intherval of pulses is more than several times larger than the field jump at each differential pulse.[5]

It is also represented in Table 8. that the rate of field change seems to be much larger at each differential pulse than in the interval between the pulses, but it is said here also that the accuracy of measured value is not sufficient to obtain a deciding conclusion from these few data obtained.

During the discharge to ground it was observed the larger number of main discharge type wave-forms than that of leader discharge type wave-forms. This, however, will be attributed to the delay of starting device of wave-form recorder, by which the wave-forms of atmospherics are reproduced on C.R.T. screen every time at the instance of their occurrences. As the instrument used was designed to record the wave-forms from far distant origins, it was neccessary for our observation of wave form of nearby lightning discharge to ground to limit the starting level of the recording device. Accordingly the device can not act at the leader stroke but acts at the return stroke in many cases when the nearby lightning discharge to ground appears. In addition to this limitation, the over-all gain of the instrument in such cases must be attenuated to a extraordinary lower value by lowering the height of vertical antenna, of which effective height is estimated to be of the order of several ten centimeters. These two lightning observation techniques were necessary for us to limit each recorded wave-form to correspond to the record of Boys' camera and to prevent the over scale on recording C.R.T. screen. Consequently it is difficult to estimate the accurate values of the field strength represented by return strokes of the observed lightning to ground. To prevent these faults of the instrument with wide band linear amplifier it will be necessary to redesign the instrument to have an adequate amplifier for the recording of leader radiation field and to change the starting device to act at still more earlier stage in step leader stroke. Through these alterations we may have a chance to record the whole situation of the leader radiation field produced by lightning discharge to ground.

Although the simultaneously linked observation of the wave-form and the lightning by Boys' camera method is difficult according to the fewer chances of lightning occurrences in Japan, a few data, however, were obtained in Summer 1952 at the thunder-storm in day time. The moving camera record photographed in day time is of course insufficient to record the fine structure of low luminosities like as that of leader stroke or component of return stroke because of the general fogging on the sensitive film, the portion of return stroke of high luminosity, however, can be catched easily by the method just described. Fig. 10 and 11 represent the sketches of the Boys' camera photographs and the corresponding wave-forms which were obtained simultaneously during the day time thunder-storm 10th August 1952 at our observation station in Maebasi city. Fig. 10 correspond to a double stroke lightning to ground which occurred at the place 20–25 km apart from the observation station. Although the moving camera photographs recorded neither the leader stroke nor the evident component of return stroke, the main parts of the return stroke could be photographed, and the latter will be seen in photograph to have some spread width which reduces with the distance from the earth to the upper cloud end of the channel. The value of the spread width at the lower end of the stroke are measured to have the value of about 0.2–0.3 milli-seconds for both cases which may be considered to represent the duration of the branch component

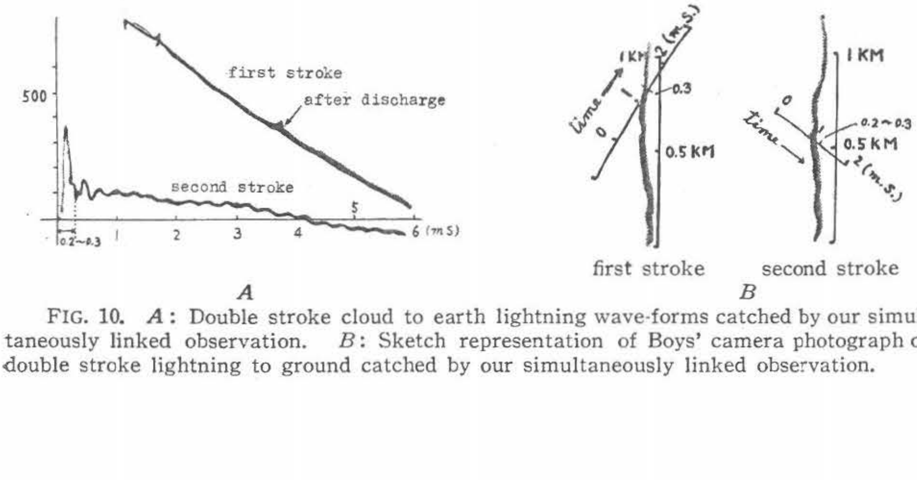
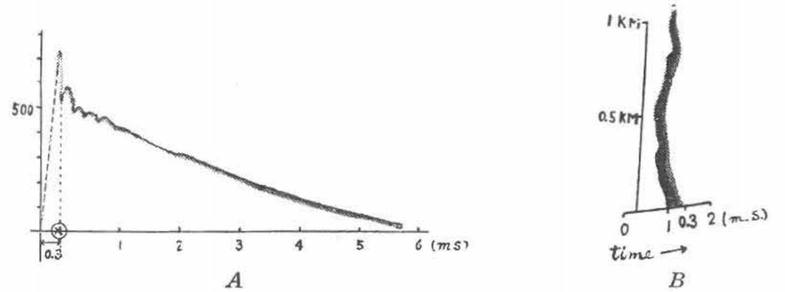


FIG. 10. *A*: Double stroke cloud to earth lightning wave-forms catched by our simultaneously linked observation. *B*: Sketch representation of Boys' camera photograph of double stroke lightning to ground catched by our simultaneously linked observation.



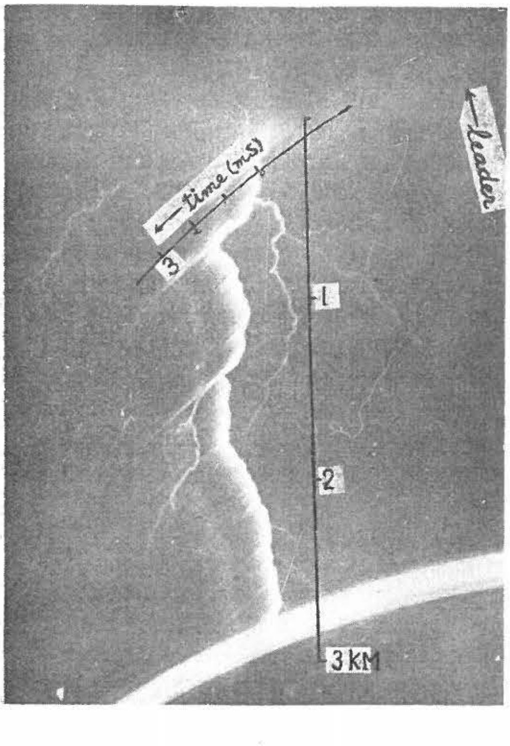
A *B*

FIG. 11. *A*: Wave-form of single stroke lightning to ground obtained by our simultaneously linked observation. *B*: Sketch representation of Boys' camera photograph of single stroke lightning to ground obtained by our simultaneously linked observation.

of the return stroke.[11] The corresponding top portion of the wave-form for the first return stroke was missed in our oscillographic record, the second return stroke, however, was catched as reproduced in Fig. 10 *B*. and the first elementary wave width is measured to have the value of about 0.2-0.3 milli-seconds for the second return stroke. Fig. 11 represents the case of the single stroke discharge to ground obtained at the same thunder-storm as that of Fig. 10 and the distance of the lightning channel from the observation station was also nearly the same as that in the former case. The duration of the return stroke obtained from Fig. 11 *B*, at the earth end is about 0.3 milli-seconds and the corresponding first elementary wave width of the wave-form is also nearly 0.3 milli-seconds. Hence it will be reasonable to conclude from the results just obtained that the first elementary wave of the atmospheric wave-form which corresponds to the lightning discharge to ground is emmitted from the main part of return stroke of a lightning to ground. This is the conclusion which was already supported by Lutkin[2] and Schonland.[3] It is, however, a matter of question at present that the wave-form of return stroke does not represent the character of clear differential pulses which correspond to the return stroke as well as to the following components of a lightning discharge to ground. The duration or width of the surmised pulse of return stroke and those of components of return stroke may be supposed to be of the order of 50-200 micro-seconds from the result obtained by Boys' camera method.[11] This is clearly larger than the interval between the supposed leader streamer pulses, *i.e.*, 30-90 micro-seconds, of which frequent value is about 50 microseconds, or the pulse width of about 1 micro-second and more-over the over-all gain of the wave recording instru ment was attenuated to a extraordinarily lower value in the case of observation of lightning discharge to ground compared to the case of intra-cloud discharge in cumulo-nimbus. Hence the peaks of the surmised differential pulses of return and component strokes will be reproduced more rounded on C.R.T. screen than those of leader stroke pulses, and this may be the reason why the wave-form of the return stroke does not represent the differential character.

The small pulsive waves which occured just after the return stroke are seen on the first stroke wave in Fig. 10 *A*, but it is not clear whether these correspond to the Malan component of return stroke. Our Boys' camera investigation of lightning in this summer points out the mean duration of return stroke at the earth end to be roughly 0.5-0.7 milli-seconds the mean duration of M component to be nearly 0.8 milli-seconds and the whole return process to finish in 2 milli-seconds or so in most cases. Fig. 12 is one of the example of our several Boys' camera photographs, being composed of a single stroke, of which distance from the observation station is roughly 20 km. The leader duration estimated to be roughly 5.5 milli-seconds and the channel length to be about 3 km, therefore the calculated leader velocity of 5.4×10^7 cm/sec. represents a reasonable value as a mean stepped leader velocity. The return stroke duration at the earth end is 0.5–0.7 milli-seconds, the M component duration is about 0.8 milli-seconds, and the whole return process ceases roughly within 2 milli-seconds. On the other hand the small pulse on the wave-form of the first stroke in Fig. 9 *A* occurs roughly 3.5 milli-seconds after the first return stroke is over and the pulse width is estimated to be roughly 0.2–0.3 milli-seconds, hence it will be reasonable to surmise that the small pulse following to the wave of return stroke corresponds to 'partial discharge' in the cloud which appears after the main lightning discharge is over as pointed out by Norinder,[12] or is radiated during J-process observed by Schonland and Malan.[13]

It is an interesting problem to compare the wave-forms of lightning to earth during the thunder-storm and those of main stroke type in calm days, when we consider the problem of electro-magnetic wave propagation. According to Schonland[3] there must be atmospherics at night of which wave-forms can be considered to be composed of a single rectangle wave, hence some atmospherics at day-time which are produced from near lightning discharge to earth must have the wave-form of which first elementary wave amplitude is conspicuously larger than that of the following elementary waves. Fig. 13 represents the percentage number distribution of the ratio of the first elementary wave amplitude to the second elementary



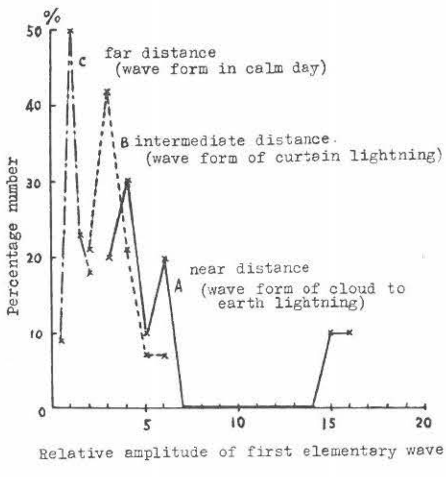


FIG. 12 (*left*). An example from our Boys camera photographs obtained in summer 1952.

FIG. 13 (*right*). Percentage number distribution of the ratio of the first elementary wave to the second in main discharge type wave-form.

wave amplitude of main discharge type atmospherics. When the curve A, which corresponds to lightning discharge to earth during thunder-storm is compared with the curve C, which represents the case of typical smooth main discharge type wave in calm day, it will be found that the relative amplitude of the first elementary wave in the former case is generally greater than that in the latter case, and that in 20 per cent of the former case the ratio reaches to the value of more than ten. In addition to this, it will be also seen from the same figure that the relative amplitude of the first elementary wave of the main discharge type atmospherics decreases gradually with the distance of discharge channel from the observation station, if we compare the curve A which represents the case when the thunder clouds situated over-head to the curve B which represents the case when the same thunder clouds moved to a distance of the order of several ten kilometers. It is, however, not evident at present either this variation in fine structure comes from the change in discharge character with the life of a thunder-cloud or this is influenced by the effect of propagation of electro-magnetic wave through atmosphere.

IV. Main Discharge Type Wave-Form in Calm Day

The typical wave-form of main discharge type[14] has the character of a smooth quasi damped oscillation, of which example is reproduced in Fig. 14. This type is generally observed more frequently when the thunder-storms are not reported within the area of about 100 kilometers from the obsevation station, than when they are reported in the same domain.[15] The rate of occurrence of this type wave-form often reaches 5-6 wave/min., when there are reported no evident thunder-storms within the domain of about 100 kilometers from the observation station, even if the over-all gain of the instrument is limited to the value which is unable to record the waves from far distant origins. As the frequency of cloud to earth lightning occurrence is observed to be about 1–2 times per minute, it may be reasonable to consider that the wave-forms which are ordinarily considered as to be radiated from the main stroke of lightning discharge to earth, actually comprise the wave-forms which must be supposed to be radiated from small scale discharges in thunder-cloud having a kind of main discharge character. The wave-forms which are presumed to correspond to these small scale dicharges having main stroke like character will have generally shorter duration, *e.g.*, less than 400 micro-seconds compared to the typical main stroke type wave-forms, of which duration reaches frequently to more than 1,000 micro-seconds. Hence we have treated the latter as the partial discharge type wave-form following to the idea proposed by Norinder[12] in the preceding paper.[16] The variation of the relative quasi half period with the order of the half waves is represented in Fig. 15 to compare the differences between these wave-forms in calm day and under thunder-storm. Curve A and B correspond to the wave-form of long duration, *i.e.*, the main discharge type, and to that of short duration, *i.e.*, the partial discharge type in calm day, respectively. The relative half period is seen to increase in both cases with the order of the elementary half waves, but the curve reaches faster to a stationary value in the case of shorter wave than in the case of longer one. The curve C and D correspond to the main stroke type wave-forms during thunder-storm, in which each wave-form is identified with each curtain lightning at distance of roughly several ten kilometers from the observation station. Therefore it is

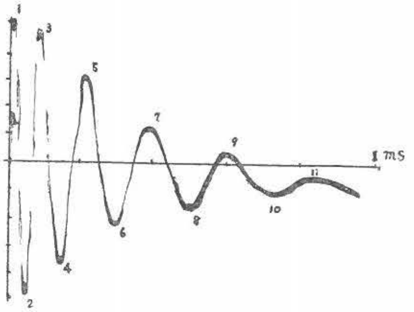


FIG. 14. The typical wave-form of main discharge type in calm day.

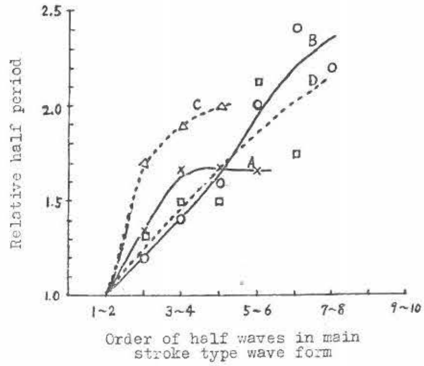


FIG. 15. Variation of relative half period with the order of half waves.

evident that the wave-forms obtained correspond to lightning to ground as well as to cloud lightning at the distances just described. Curve C and D are classified from the stand point whether the duration of the main discharge type wave-form corresponding to the lightning has the value of less than 400 micro-seconds or it has the value nearly of 1,000 micro-seconds. From the analogous tendencies between the curves A and C as well as between the curves B and D it may be concluded perhaps that both wave-forms of main discharge type character having shorter and longer durations similarly correspond to cloud lightning as well as to lightning discharge to ground in a thunder-storm.

V. Conclusion

Although the deciding conclusion is not obtainable at present by the insufficient number of observed data at our disposal, it will, however, be concluded from the above discussions on fine structures of atmospheric wave-forms as follows:

1. The wave-forms radiated from intra-cloud discharge in sufficiently grown up cumulo-nimbus represent the character of small pulsive wave train which may be considered as to correspond to the stepped leader streamer of air or cloud discharges, but the pulses of large amplitude which are superposed on the whole small pulsive wave train just described should be interpreted as to correspond to the dart leader like streamers of multiple character which present themselves simultaneously with the stepped leader streamer that composes the main part of a violent discharge in the cloud.

2. The leader wave-form obtained from the over-head lightning to ground shows the clear pulse wave trains, the former half part of which represent the character just analogous to the case of intra-cloud discharge on one hand, the latter half of which represent the pulse intervals explainable from the stepped leader structure of a lightning to ground on the other hand. The main stroke type wave form which corresponds to lightning stroke to ground photographed by Boys' camera method shows that the width of the first large pulse in the wave-form correspond to the duration of main part of return stroke measured at earth end. The small pulses occurring after the main part of the wave-form has passed by are

presumed to correspond to the small discharges in the cloud after each stroke of lightning discharge to ground has beer over.

3. It is surmised from the analysis that the main stroke type wave-form can not always correspond to the main stroke of a cloud to earth lightning but also correspond to a special type of discharge in the cloud.

VI. Acknowledgement

This paper is prepared from the data obtained through the thunder-storm observation at Maebasi city in summer 1952 and 1953. Authors express their sincere thanks to menbers of Telegraph and Telephon Office at Maebasi city for their kindness affording the facilities for our thnunder-storm observations. Our thanks are also due to Prof. Kimpara, Director of our Institute, to Prof. Honda at Univ. of Tokyo and to Dr. Hatakeyama, Director of Meteorological Research Institute for their interests on this study and the valuable discussions on several points in the present paper.

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