ON THE LEADER WAVEFORMS OF ATMOSPHERICS NEAR THE ORIGINS

By

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Synopsis.

The authors have adopted the discontinuous method of recording the atmospheric waveforms, in which each waveform, singly swept on the screen of respective C. R. T., is photographed in the respective frame of 35 mm cine film. These techniques have made it possible to perform an uninterrupted recording of waveforms throughout the period of a thunderstorm often lasting more than several hours, and to deduce statistically more general features common to a certain type of lightning discharges than the continuous method of recording can do. Following these views the authors have made a statistical analysis of waveforms obtained under thunderstom conditions.

It has been made clear through the present analysis that:

(1) Almost 80% of the recorded stepped leaders preceeding ground discharges has been found to be β type, and this situation has not been changed through two years' observations.

(2) Positive space charges presumed to exist at the thundercloud base really activate the formation of β type leaders, neverthless, α type leaders can often be produced even in such cases, where a clear evidence exists that a strong positive space charge centre is present at the cloud base.

(3) The nature of the initial portion of a stepped leader is the same for both these two types, and the time interval values between two successive pulses in this portion clearly reduce from larger values, more than 100 μs, to normal values, roughly 50 μs, when the leader steps out of cloud base and develops in the gap between cloud and ground.

(4) In some cases a β type leader, followed by a return stroke, produces a train of small pulsations in its final few ms, just before the return stroke appears. The mean time-interval, roughly 20 μs, of these pulsations is clearly smaller than the normal value between step streamers. It is not clear at present whether each of these final pulsations is produced by a step streamer appearing in the last stage of leader development, as the Boys' camera photopraph of a typical α type stepped leader does not represents any reduction of step intervals throughout the final stage of it at all.

I. Introduction.

When the progressive velocity of a fast stremer involved in a lightning discharge reaches the value of the order 10^9 cm/s., the radiation field changes caused by it becomes very strong (1) and the waveforms come to represent a prominent pulsive form of a differential type.

The pulses thus produced can be considered to compose the complicated waveform of an atmospheric at its origin, as the complicated group of such fast streamers usually forms up a lightning discharge. Hence it is to some extent possible statistically to deduce the nature of the discharges by analysing pulsive waveforms of atmospherics near their origins.

II. Recording apparatus.

The recording of an atmospheric waveform is triggered with a high frequency component, selected from 0.1, 1 and 10 Mc/s., of the same atmospheric. To perform the action the frequency component is amplified through a superheterodyne type amplifier, the gain of which is adjustable independently to that of the main amplifier, and singly triggers the waveform on two sets of C. R. T. and 35 mm camera systems, the time bases of which are 2 ms. and 20 ms. respectively (2). The effective height of the vertical antenna employed is 2 m. and a metal sphere with diameter 7 cm. is attached to the top of it to prevent surplus point discharges from it. As the pair of waveforms can be recorded at an independent sensitivity from each other, we can investigate on the record of short time base the fine structure of the initial 2 ms. portion of the long time base. This discontinuous method of waveform recording has an advantage over the continuous one, in that the former enables us to record lightning discharges throughout the period of a thunderstorm that often lasts more than several hours and thus we can obtain a more general view about the lightning phenomena from the statistical point of view.

III. Typical examples of waveforms recorded.

Fig. 1. shows three typical examples of waveforms recorded by the present technique of triggering method using 1 Mc/s. frequency component of the discharge and they were recorded during a thunderstorm observation in summer 1956. Figures (A) and (A′) represent the waveform which was confirmed by visual observation to come from a ground discharge roughly 25 km. apart from the station. Waveform (A) represents the whole variation of this discharge from the first leader to return stroke and (A′) the fine structure in the initial 2 ms. section of waveform (A). Waveforms (B) and (B′) also represent the first stroke of a ground discharge, the leader section of which carries prominent pulses throughout the period of the leader. Therefore the waveforms evidently come from the ground discharge initiated with a "α type" stepped leader. Waveform (C) and (C′) represent small complex variations of elecrto-static field, and the initial section of it carries several negative pulses, as (C′) indicates. The nature of the pulse train is, however, very different from that of the first leader as illustrated in (A′) and (B′), hence the waveform must be considered to be produced by a discharge within thundercloud. Fig. 2 illustrates the ground discharge with a clear β type stepped leader. The leader of this discharge carries a clear train of differential pulses in the initial portion of it, but it vanishes towards the rear portion of it as time goes on.

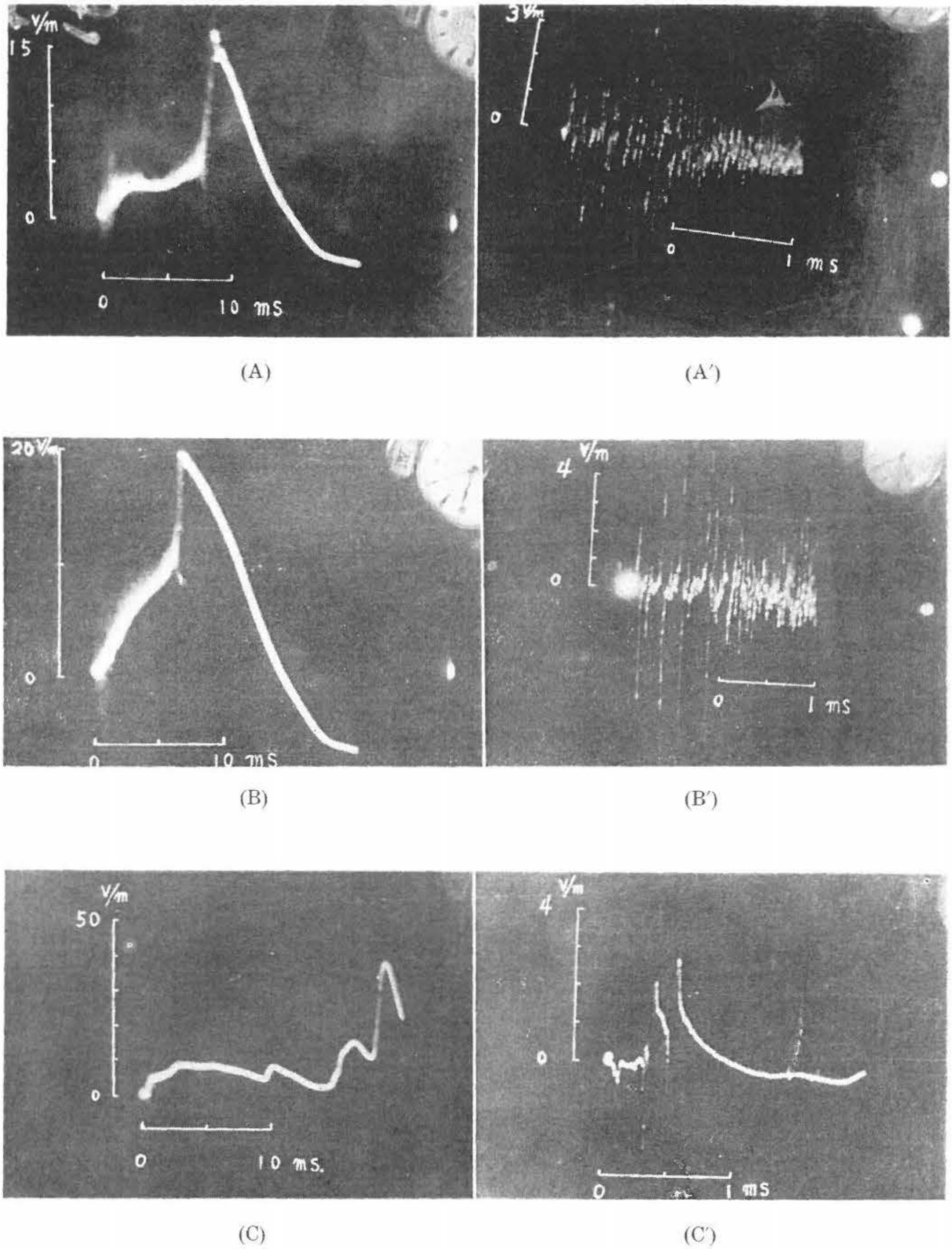
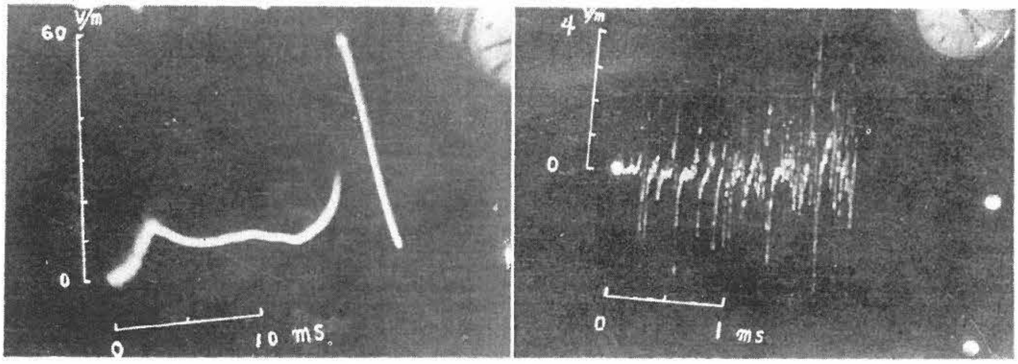


Fig. 1. Example of waveforms recorded by the trigger method.



(A) (A′)

Fig. 2. Slow electro-static field change on the leader section of a ground discharge with β type leader.

IV. Leader field change.

Two types of leaders. In the present apparatus the ground discharges, even if multiple, are triggered at a pulsive portion of the first leader, as the action of recording the electric field variations is initiated by a high frequency component selected from three involved in itself. So the return stroke caught by the apparatus must be the first stroke. There are 87 records which succeeded to receive the ground discharge from leader to return stroke, and 69 records each of which represents a prominent stepped leader but without return stroke. The latter must involve the case in which the first leader of a ground discharge is longer than 20 ms, as well as the case in which the stepped leader does not reach the ground and ends itself as an "air discharge". Each of all these 156 waveforms has a leader section that carries numerous differential pulses on it. These stepped leader waveforms can be classified into two types, i. e., α type and β type, according as the pulses appear throughout a leader section or vanish midway. The experimental result of the year 1956 is given in Table 1. along with that of 1955 (1). The result of 1956 shows that 8% of the recorded stepped leaders are α type and 77% of them β type. The ratio of the number of α type to that of β type in 1956 is 1.1/10, which is not so much different from 2/10, the ratio in 1955. This indicates that as much as 80-90% of the stepped leaders occurring in our country are β type, which seems to be one of the principal reasons why the photograph of a clear α type stepped leader has not yet been obtained by Boys' camera in our country since the employment of this technique in the observations of lightning flashes (3).

Slow leader field change. As the resultant time constant of the amplifier to record 20 ms waveform is about 4 ms, the nature of the slow field changes characteristic of the advancing negative pilot streamer can roughly be analysed on each record, provided that the discharge concerned is generated roughly within the range of 40 km from the station and the time rate of slow field changes at the station is sufficiently large to produce measurable deflection of bright spot on C. R. T.'s of the recorder.

In a downward journey from the interior of a thundercloud to the earth's

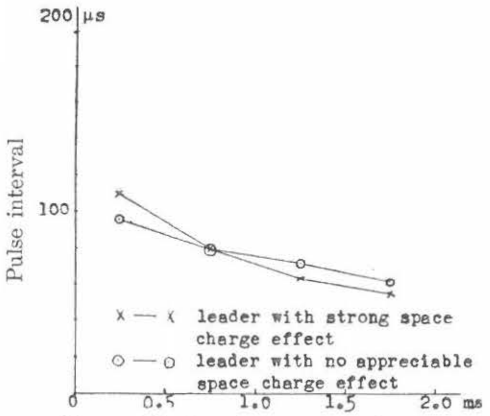
Table 1. The number of the two types of stepped leaders recorded.

Year of observation	Type of stepped leader		
	α type	β type	Intermediate type
1955	2	10	5
1956	13	120	23

surface the stepped leader abruptly slows down its speed of progression, once it reaches the positive space charge now generally assumed to exist at the thundercloud base, which is one of the important characteristics of β type stepped leader (4). Correspondingly the slow field change produced by β type stepped leader is not uniform, but carries a clear fold point on it (5) in contrast to the case of α type, in which the field change is uniform and roughly represented by $F=at^2$ (4), if the distance of the discharge from the station exceeds the reversal distance, i. e., roughly 6 km. Fig. 2 illustrates the typical slow field change due to β type leader 6–19 km apart from the station. There are 73 waveforms which represent ground discharges from leader to return stroke and carry slow field changes of the type $F=at^2$ on their leader sections. As the distances of these waveforms are roughly estimated at less than 40 km except for a few cases by employing Morrison's method (5), we may say statistically that these 73 discharges occurred within the range 6–40 km from the station. These 73 stepped leaders can be separated into two classes according as the record has or not the fold point on the leader section, i. e., the field change due to a space charge. The result is summarized in Table 2, which shows that 76% of 54 β type stepped leaders each have a fold point, but it becomes 62% in the intermediate type, and 33% in α type. Therefore it is evident that the number of stepped leaders having been recorded and representing the strong snfluence of the space cnarge is the largest for the case of β type leaders. This mens that the positive space charges, if they are very strong, change most of the stepped leaders into β type (4). However, the table further shows that 24% of β type leaders has no detectable space charge effect, and 30% of α type leaders is appreciably influenced by it. This indicates that the positive space charge at the cloud base, really can bring about the formation of β type leaders, provided the degree of the charge accumulation at the cencerning point being extraordinarily high; however, it can not change all the leaders into β type, when the accumulation is appreciably but not exceptionally high. In the latter case the leader from the interior of a thundercloud will be changed into β type in one instance, or not changed and remains as α type or intermediated type in another.

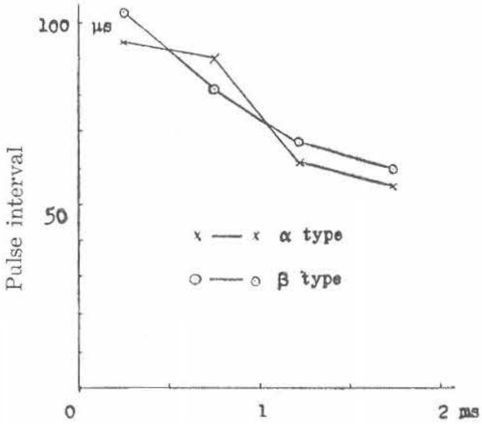
Table 2. Slow field change produced by stepped leaders.

Types of leaders	No. of leader records		
	With no measurable space charge effect on leader section	With space charge effect on leader section	Total
α type	4	2	6
β type	13	41	54
Intermediate	5	8	13



Time of leader discharge development

Fig. 3 The influence of space charge on the variation characteristics of pulse intervals with time of β type leaders.



Time of leader discharge development

Fig. 4 The relation between leader types and variation characteristics of pulse intervals with time.

Leader pulse. Generally the time interval between two successive pulses on the initial portion of the leader waveform reduces as the time goes on, which point is represented Fig. 3 and 4. These figures are obtained as follows. The waveforms representing the field changes from leader section to return stroke were selected on 20 ms records, and the initial pulse intervals were measured on the corresponding 2 ms waveforms. The time base of 2 ms waveforms was divided into 4 equal sections and the mean time interval in each 0.5 ms section was calculated. The variation of the mean pulse interval value with time from the beginning of the leader waveform is plotted in the figures. Fig. 3 shows the average, in total, of 47 β type stepped leaders, and the pulse interval characteristics are compared between 25 leaders representing the appreciable space charge effects on themselves, and 22 leader with no measurable space charge effects. The distances, in total, of 83 ground discharges including those involved in Fig. 3 and 4 are roughly estimated at less than 50 km with Morrison's method as before, and 83% of them are less than 30 km and 90% less than 40 km. The amplifier gain employed to receive the waveforms of Fig. 3 was adjusted to 5–23 db. Hence the leaders which have no detectable fold point on themselves mean that there were no appreciable positive space charge existing at the cloud base. According to Fig. 3, the pulse intervals on the initial portion of β type leaders reduce from about 100 μs to 60 μs in both cases as time goes on. So that the existence of the space charge does not change the pulse outbreak nature at the initial portion of β type leaders at all. This probably means that the discharge mechanisms of fast streamers at the beginning of a β type leader are not changed by the presence of a space charge. In Fig. 4 the same average pulse nature as Fig. 3 is compared between 9 α type leaders and 64 β type leaders. The intervals here again reduce with time roughly from 100 μs to 50–60 μs, and no appreciable differences exist between these two types of stepped leaders. It is striking that the frequency of differential pulses, which may be presumed to be emitted by fast streamers, increases with time from the beginning of stepped leader independent of the types.

According to the result obtained with Boys' camera (6) the pause time of successive step streamers of α type leaders are kept remarkably constant, throughout the period when the leader progresses the space between cloud and ground. To see the variation of step pause time with progress of leader in the final stage of it the Boys' camera photograph (flash 76), illustrated in Schonland's paper (6), of a clear but appreciably fast α type stepped leader has been employed, and the time intervals have been measured on it. The result is reproduced in Fig. 5, in which time is measured backward from the momet of start of return stroke. The figure clearly shows that this typical leader has normal step pause times with the mean value 52 μs, so far as it progresses through the space between cloud and ground, and the situation is kept the same onto the moment just when the return stroke is going to start. The estimation of the leader velocity of this leader gives the value 1.7×10^{8} cm/s and is about 10 times larger than statistically normal values of leader progression. It is evident from these facts that α type leaders at their initial stage of development have appreciably long time intervals between successive fast streamers, more than 100 μs, so far as the leader discharge takes place inside the thundercloud. But, when the leader has once stepped out of cloud base, it reduces rather abruptly to the normal value of about 50 μs, the value which is characteristic of α type leaders travelling down the discharge gap between cloud base and ground. Correspondingly the waveform of α type leaders must have normal pulse intervals through the rear half period to the moment just when the return stroke starts, except for its initial portion with long intervals. This variation of pulse intervals with the development of leader dischage is incompatible with the uniformity of progression of α type leaders; therefore the fact seems strongly suggestive that the initial portion of α type leader with long pulse intervals does not correspond to the beginning portion of the intrinsic α type leader, but produced by cloud discharges composed of successive fast streamers leading to the initiation of an intrinsic α type stepped leader (4). Moreover, as the variation of pulse intervals with time in the initial portion of stepped leaders is the same for both of α and β type leaders, and not influenced by the presence of positive space charge at the cloud base, the initial pulses appearing on the top of β type stpped leaders must also be considered to be produced by cloud cischarges similar to that of α type.

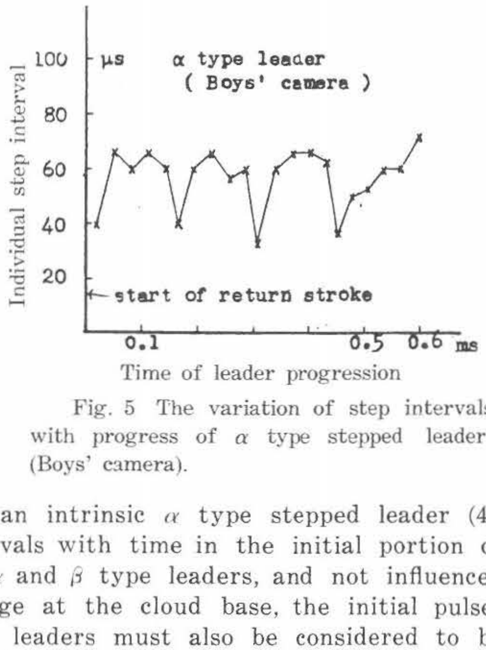
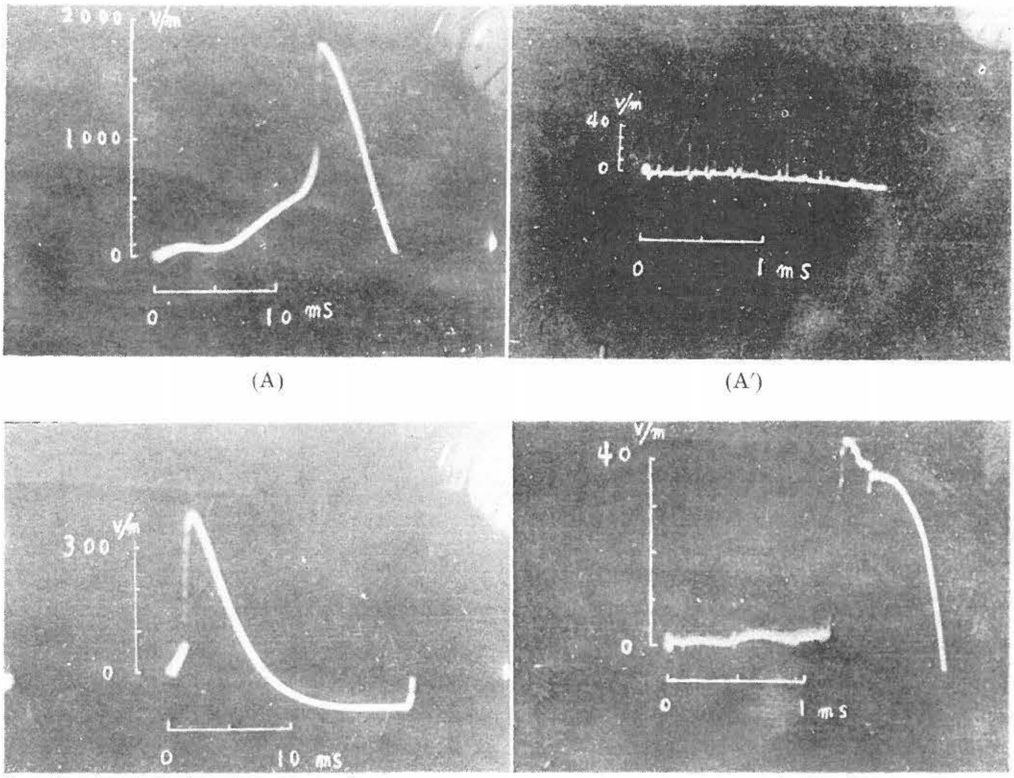


Fig. 5 The variation of step intervals with progress of α type stepped leader. (Boys' camera).

Final portion of stepped leader. Although the waveform of β type leader followed by a return stroke has the prominent initial pulses in its first several ms, the amplitude of these pulses diminishes rapidly with time towards the rear half of it, and finally return stroke appears. This situation is illustrated in Fig. 6 in which (A), (A′) show the initial portion of β type leader and (B), (B′) the final portion of it respectively. As the ground discharge illustrated appeared at



(A) (A′)

(B) (B′)

Fig. 6

distances about 10 km away from the station, the amplifier gain of the waveform recorder was limited to -17.1 db in the case of (A′) and to $+3.3$ db in the case of (B′), which is very lower than that of Fig. 1 (A′), (B′), (C′) and (D′), i. e., 22.5 db. Hence the small pulsations superposed on large initial pulses are not recorded in a measurable degree. The final portion of the leader shown in Fig. 6 (B), (B′) has not any large pulse similar to the initial pulse, but small pulsations with higher repetition frequencies are seen throughout the portion. To see the point further, we have selected β type leader waveforms, each of which is followed by a return stroke and initiated with a clear initial pulses, and examined on 20 ms waveforms whether they have final small pulsations or not. The result obtained from the records of 1956 and 1957 is summarized in Table 3. In the table the distance of

Table 3. Final pulsations appearing at the end of β type stepped leaders.

Distance of discharge	Number of β type stepped leaders recorded	
	With final pulsation	With no measurable final pulsations
6- 10 km	1	8
15- 40	21	22
80-150	3	18

the ground disdharge has been estimated from the rough relation between the distances of thunderstorms obtained with a thunderstorm map kindly offered us by the Meteorological Observatory and from the gain of the recorder amplifier (7), as well as from Morrison's method. Table 3 shows that 10–20% of the ground discharge waveforms with prominent initial pulses at their top portions has final pulsations just before return stroke arises, and the situation does not vary with the receiving distances of discharges. This means that a minority of β type leaders occurring in our country, each followed by a respective return stroke, has final pulsations at the final stage of it. These small final pulsations are seen to continue for a few ms. Table 4 represents the relation of the duration to the number of waveforms recorded within the range 15–150km from the station. It indicates that in about 90% out of 27 cases the durations are shorter than 2 ms, and 60% of them shorter than 1 ms. The mean value of these 27 durations is 1.4 ms. If we assume the velocity value in the final portion of β type leader to be 2.0×10^{7} cm/s taken from Malan's paper (8), the average distance travelled by the leader in its last stage of progression must be 280 meters* above the ground, that is, the final pulsations appear when the leader tip travels the final gap length of 280 m, remaining above the ground. It is generally known that the ground streamers exist just prior to the time when the leader make, contact with the return stroke (9), the length of these streamers reported, however, is not so long, when the leader strikes an open ground like a beach close the water. In such cases the upward ground streamer and the upward branching from the root of the main stroke do not develop more than 2.5 m above the ground. All the Boys' camera photographs, obtained by us, of the ground flashes also do not represent any prominent root branching of the lightning channel; therefore it is evident from our Boys' camera data that an upward streamer from the ground, if it exists, does not develop more than 20 m above the ground in our case. Moreover these ground streamers may not occur before the pilot streamer tip reaches the point no more than 40 m above the ground, as the spark discharge develops from both electrodes to meet each other at the middle part of the gap space between two rods subjected to a high impulse voltage. This means that the pulses due to these ground streamer, even if they exist, can not present themselves from the moment more than 200 μs before the start of return stroke, as the leader develops its last 40 m in 200 μs in the average. Hence these upward streamers from the ground seem to be insufficient to interpret the final pulsations of β type stepped leaders. The pulse intervals in the final portion of a stepped leader have been measured on 2 ms waveforms which represent the field changes due to a ground dischare from final portion of leader section to return stroke, and which can be considered to be triggered by the final pulsations of β type leader lacking prominent initial pulses on the top of it. The results obtained

Table 4. Duration of final pulsations

Duration of final pulsations	Number of waveforms recorded
0–1 ms	16
1–2	8
2–3	2
3–4	1
4–5	0

* This value may be rather small as a mean value, for the progressive velocity of a stepped leader generally increases in the final stage of it according to the increase in electric field (4).

from two years' observations are summarized in Table 5, in which the time intervals represent the mean values obtained from 6 records for the case of 6–10 km, 3 records for 15–40 km, and 5 records for 80–150 km respectively, and the distances of the discharges have been estimated as before. Considering the accuracy of the time interval measurements, we can see that there is no evidences that the intervals vary with receiving distances of waveforms. This means that the leader produces successively fast streamers with mean repetition time interval 20 μs in the final, in average, 1.4 ms of its progression. The velocity of β type leader, its step length, and luminosity, suddenly reduce, when the leader tip reaches a space charge centre existing beneath the cloud base. The step pause time intervals in the rear half of β type leaders, however, can not be measured on Boys' camera photograph owing to the too faint luminosity of it to catch the details of the discharges (10). Hence we have no direct knowledges about the time intervals between successive step streamers in the rear stage of β type leaders. If the time intervals between successive step streamers in the rear half period of β type leader are, in average, the same as those of α type, we must conclude by considering the results of Fig. 5 that the final pulsations on β type leaders are not emitted by individual successive step streamers, but radiated from secondary discharges surrounding the pilot streamer head. But, if the second half portion of β type leaders has in average, step intervals, of lower values than the normal one, 50 μs corresponding to α type leaders, the final pulsations of β type leader can be interpreted by the successive step streamers. It is not clear at present, however, which of these two is more probable. The pulsation intervals of few ten μs, on the other hand, can be detected in many cases other than the final portion of β type leaders.

Table 5. Pulse intervals between successive final pulsations.

Distance of dischage	Pulsation intervals
6–10 km	26.1 μs*
15–40	19.8
80–150	20.0

* The accuracy of the time interval measurement is not high and the value seems to be too high according to insufficient gain of the main amplifier.

The small pulsation intervals have been measured on various portions of individual 2 ms waveforms, the results of which is reproduced in Table 6. The interval values represented in the table are the mean values obtained from 8 cases in the

Table 6. Time intervals between small pulsations superposed on various types waveforms.

Position of small pulsations on the waveform	Average pulsation interval	
	In the first half period of 2 ms waveform	In the second half period of 2 ms waveform
Appearing between initial pulses of β type leader followed by a return stroke	30.0 μs*	28.4 μs*
Appearing in the initial portion β type leader without any detectable initial pulses	19.7 μs	
Appearieg in the initial portion of cloud discharge waveform	21.1	
Associated with a single prominent differential pulse involved in a cloud discharge	24.9	

* The accuracy of time interval measurements is not sufficiently high.

first row, from 5 in the second row, from 12 in the third row, and from 12 in the fourth row. The first row relates to small pulsations appearing between large initial pulses on the top portion of β type leader followed by a return stroke. The second row represents the case of pulsations appearing in the initial portion of β type leader of a ground discharge, but this time, without any measurable initial pulses on the leader section. The values represented in these two rows are not identical, but if we consider the accuracy of the time interval measurements, the value in the first row is too large and the true value of it seems to approach 20 μs. This means that the discharge mechanisms emitting these small pulsations in the first and the second row are not different from each other. If the initial pulses on β type leader waveforms are produced by a stepwise mechanism of discharge in the cloud the small pulsations appearing between these initial pulses must be radiated from secondary discharge effects surrounding the charge centres or the streamer heads. This seems to support the opinion that the final pulsations of β type leaders may be produced by secondary processes surrounding the pilot streamer head. The third row of the table relates to small pulsations with the same character as that of the second row, but they are not followed by return strokes and thus compose the beginning section of a cloud discharge. So the pulsations in this case do not probably relate directly to the stepped leader mechanism. The fourth row relates to the pulsations associated with a single differential type pulse appearing in a cloud discharge. Hence the pulsations evidently produced by secondary effects associated with a fast streamer appearing in a cloud discharge and have no relations to the stepped leader mechanisms. All these facts represented by Table 6 seem strongly to indicate that these kinds of pulsations repeated with time intervals, in average roughly 20 μs, are emitted by secondary discharge processes associated with lightning streamers in large scales, i. e., stepped leader, dart leader, return stroke, etc.

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