

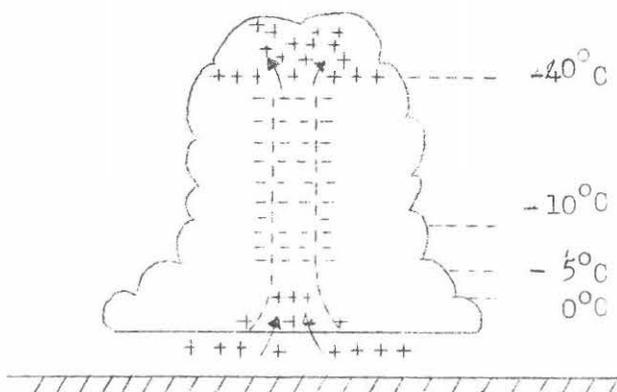
Chapter II Negative Ground Discharge

1. Introduction

It is well known that thundercloud grown up to a mature stage usually has a positive electricity P (see Fig. 1) spreading over the greater part of the top portion of a thundercloud, and a negative electricity N distributing in the lower part of the former. In the distribution of the negative electricity N, there is a portion n with high electrical charge density, which has the form of a vertical column likely extending along a strong upward converging air stream in a thundercloud. Further, in many of the thunderclouds, a small positive electrical charge distributed round the bottom of the cloud, is to be detected mostly at the portion just beneath the negative column n(1). Fig. 1 represents the electrical structure of an undisturbed cumulo-nimbus constructing a heat thunderstorm. In general, a lightning is a discharge either breaking out between the two opposite electrical charge distributions (p,p) and (N,n), or breaking out between (P,p) or (N,n), and the earth or the air surrounding a thundercloud.

Therefore, the discharge can be classified into two types, i.e., a cloud discharge which breaks out independent of the earth, and a ground discharge, in which the earth performs the function of a discharging electrode. It is in no way difficult to classify the recorded discharges into these two categories by investigating the short range CW records, because a ground

Fig. 1



discharge always has the first ground stroke composed of stepped leader followed by a return stroke, while a cloud discharge lacks this structure except for an extra-ordinary case. The investigation of short range CW records, originating in lightning discharges within the distances about 60 km from the station, shows that 28 out of all the examined 1293 CW's have intermediate characteristics lying between these two categories, and can not be classified clearly. Of the remaining 1265 CW's, the ground discharges occupy about 24 %, and the cloud discharges the remaining 76 % which point is indicated in the Table 1.

Table 1.

	Ground discharges	Cloud discharges
Percentage of the recordings	24.3 %	75.7 %
Number of CW records(*)	1265	

(*) Records originating in lightning discharges within the range of distance about 60 km.

As we shall see later (see Table 1. Chapter III and Table 18. Chapter IV), it will be reasonable to consider that most of the ground discharges break out between the charged column n and the earth, and most of the cloud discharges break out between p and n. The discharge between n and the earth lowers negative electricity (*) to the lower portion of a thundercloud, therefore we shall term a discharge a negative one or a positive one according as the polarity of an electrical charge lowered by a lightning discharge is negative or positive. Speaking of the polarity of a ground discharge, of course, both polarities are possible. However, a positive ground discharge breaking out between a small positive charge pocket p and the earth does not occur usually except for the special case. We shall first describe the nature of the negative discharge for this reason. An electromagnetic field change produced by the first stroke of a ground discharge generally has the characteristics illustrated with the electromagnetic trigger waveforms in Fig. 2. (a). As the waveforms were recorded at distances less, than 10 km from the discharges, the structure of the waveforms consists of a preliminary discharge, composed of Ig, I, and L sections, and the following return stroke R. The electromagnetic field changes due to ground strokes

* to the earth, and the discharge between p and n lowers positive electricity

following to the first, on the other hand are of the nature illustrated with the CW record in Fig. 2 (b). This is a multiple ground discharge composed of four ground strokes I, II, III and IV. The ground stroke I has just the same structure as the illustrated in Fig. 2 (a), the following ground strokes II, III and IV however, all are composed of a preliminary discharge without Ig and I sections and the following return stroke R. As the distance of the discharge is sufficiently short in this case, the electrostatic field changes due to the dart leader L₂, L₃ and L₄ of the following ground strokes all have the negative polarity, while the electrostatic field change due to the stepped leader L₁ of the first stroke represents the positive polarity. In addition, several electrostatic pulses marked with ES are seen lying in the intervals between ground strokes I, II, III and IV in Fig. 2 (b), whose meaning will be discussed later in Chapter IV. The electromagnetic field change produced by a first stroke and the lightning luminosity change corresponding to it are illustrated in Fig. 2 (c), which shows that there are appreciable light pulse emissions at times when the electromagnetic field change like Ig or L or R section comes out on the waveform.

2. The ground discharge initiated by a cloud discharge

If an electrostatic field change is observed at a distance less than 5 - 6 km from a lightning discharge, some of the ground discharges give the electrostatic field changes whose example is illustrated in Fig. 3. The field change is represented by the envelope marked with an arrow in the figure. As the record represents six stepwise field changes, so it must correspond to a ground discharge with six strokes. Except for the leader to the first stroke, no leader field change is recorded in an appreciable magnitude, because the speed of playing back the recorded magnetic tape is insufficient to reproduce the field change due to a dart leader of the duration round 1 ms in spite of a high carrier frequency 3 kc of the field meter in this case. Following what Fig. 3 indicated, it is clear that the ground stroke I has the leader L₁, however, despite of this, the discharge is not initiated with this L₁, but initiated with a discharge preceding L₁. Let us denote the first leader duration measured on an electrostatic field meter record as T_L , and the time interval between the initiation of a ground discharge and that of the first return stroke measured on the same record as T_{pp} . Of course, it is not always possible to separate T_L from T_{pp} on the electrostatic field change record of a ground discharge, however, it is in no way difficult to find a record which enables us to do it. Fig. 3 is an example of such a case. Let us assume the existence of a discharge preceding the preliminary discharge because

Fig. 2. (a)

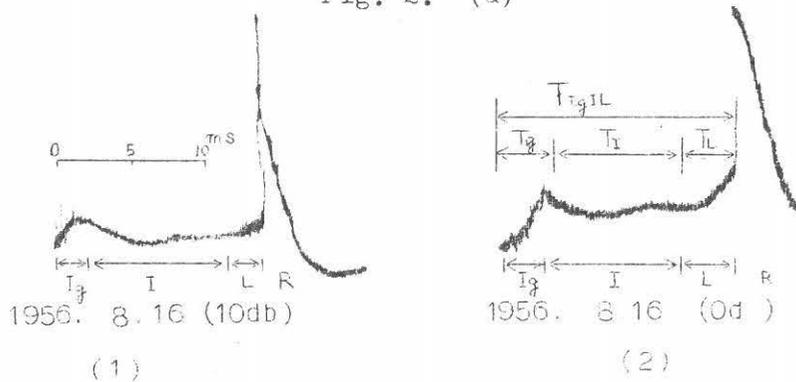


Fig. 2. (b)

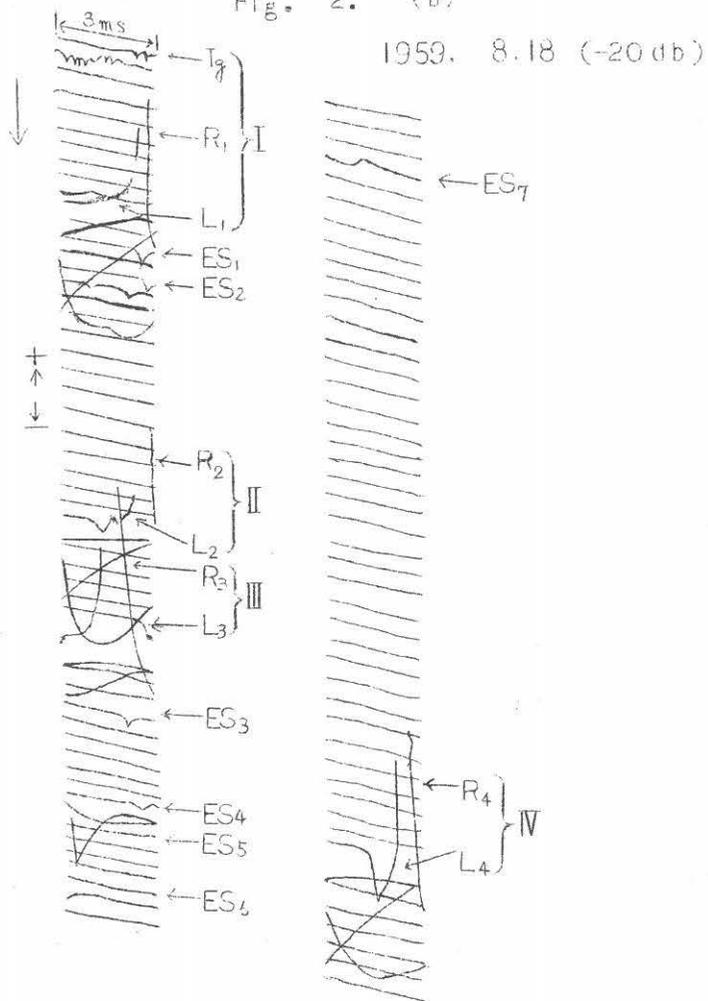
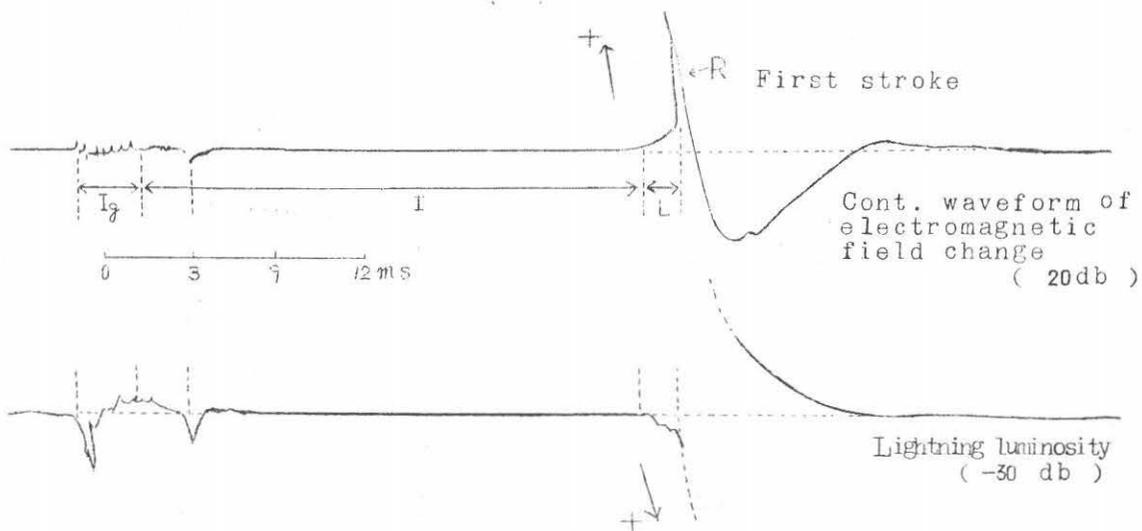
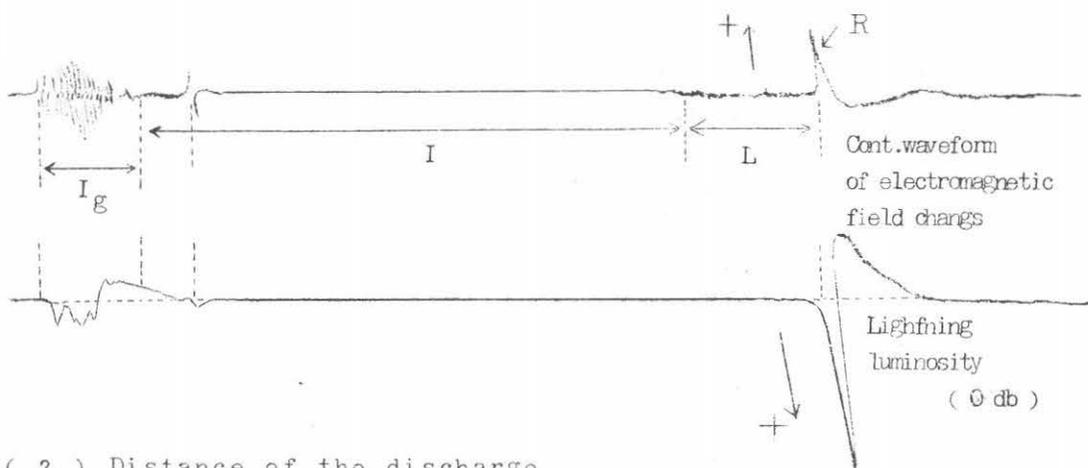


Fig. 2. (c)



(1.) Distance of the discharge
4 - 6 km

(1959. 8.13)

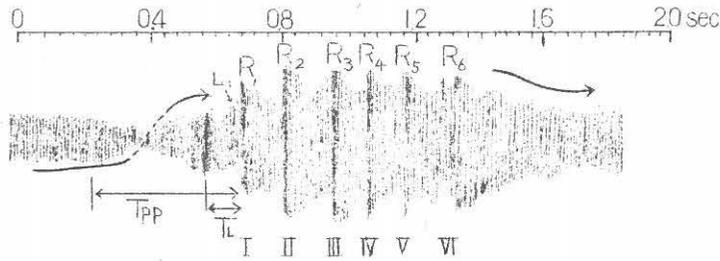


(2.) Distance of the discharge
10 - 20 km

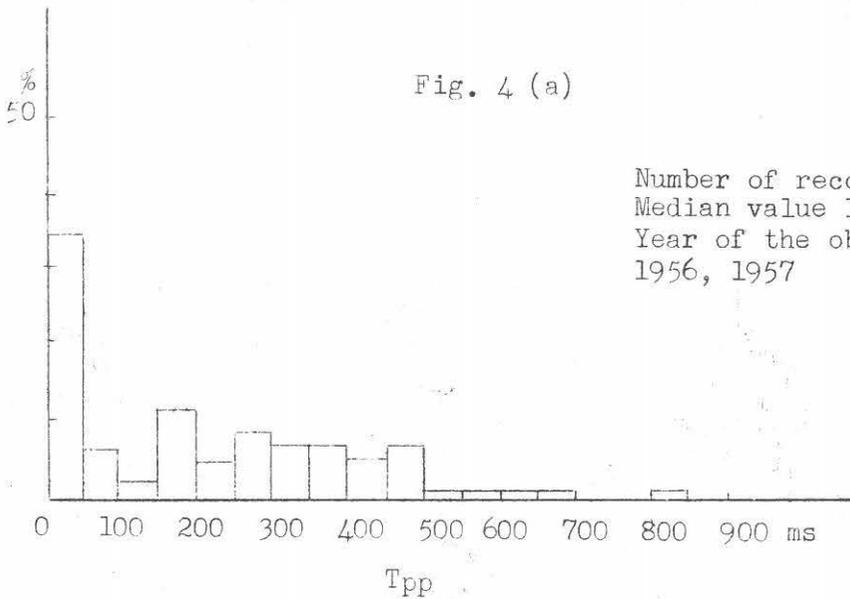
(1959. 8.18)

T_{pp} seems usually to be much longer than T_L , and term it a

Fig 3



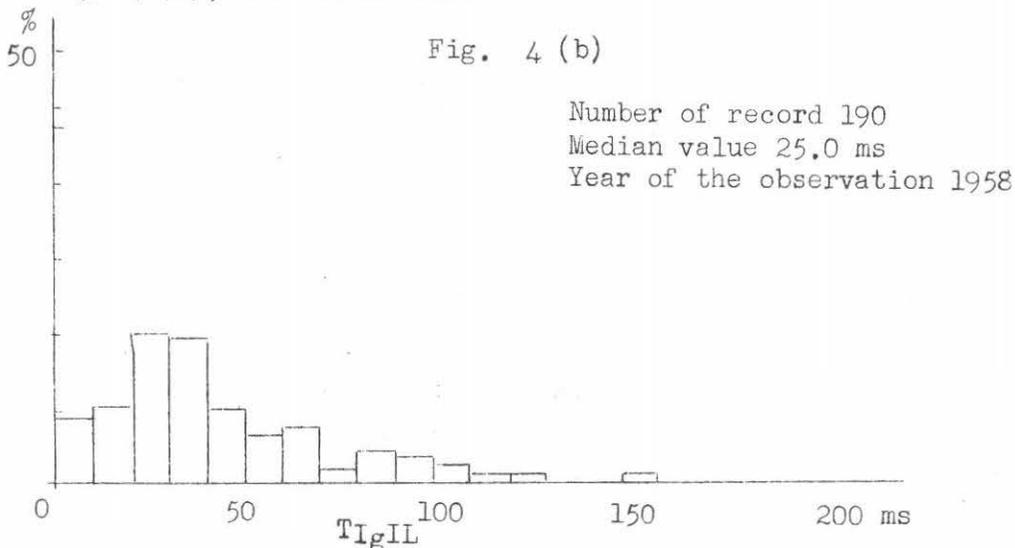
(1957 . 8 . 9 17h 15m H-20 db)



(a) Hystogram of pre-preliminary discharge duration measured on electrostatic field meter records.

pre-preliminary discharge.

To see the relation between a preliminary discharge and pre-preliminary discharge from the statistical stand-point of view, T_{pp} values* were measured on the respective records of electrostatic field changes due to 96 ground discharges occurred within distances roughly less than 12 km from the station. The hystogram of these T_{pp} values is represented in the Fig. 4 (a), the median value of which amounts to 177 ms.



(b) Hystogram of preliminary discharge duration (limited to the case of β type leader) measured on CW record of atmospherics.

For the sake of comparison, the preliminary discharge duration T_{IgIL} (see Fig. 2 (a)) has been measured on about 190 waveforms of the electromagnetic field changes due to ground discharges and the statistical result of this measurement has been summarized in the hystogram represented in Fig. 4 (b). The distribution gives a median value 25.0 ms. The comparison of these two median values clearly gives the result $T_{pp} > T_{IgIL}$, which means that we must assume the existence of a pre-preliminary discharge to interpret these large T_{pp} value. We shall first examine

* The time length between the initiation of a ground discharge and the breaking out of the first return stroke has been measured irrespective of the existence of a L field change on an electrostatic field-meter record.

how many of the ground discharges being initiated really by a pre-preliminary discharge. As the maximum value of T_{igII} indicated in the distribution given by Fig. 4 (b) is 160 ms, a ground discharge with T_{pp} value greater than 160 ms must be considered to have a pre-preliminary discharge. As the percentage number of the discharges with T_{pp} values exceeding 160 ms, estimated from the data of Fig. 4 (a), is 53.2 %, hence at least 53.2% of all the ground discharges recorded with our electrostatic field meter must have each a pre-preliminary discharge. To see whether a pre-preliminary discharge has a special character or not, we have investigated the fine structure of it on the record of electromagnetic field change due to a ground discharge whose preliminary discharge does not present itself till to the half way of the discharge. However, we have not succeeded to find any special characteristic other than that of an ordinary cloud discharge to exist in the initial portion of the field changes. Therefore it will be reasonable to conclude that a pre-preliminary discharge is nothing but a certain cloud discharge preceding a ground discharge. Table 2 (a) shows the percentages of our electromagnetic records of ground discharges each initiated by preliminary discharge together with those of the records of ground discharges each initiated by a cloud discharge year by year. The table tells that the percentages of these two do not vary in an appreciable magnitude from year to year. Concerning the ground discharges each initiated by a cloud discharge, the percentage 24.5 % given in the Table 2 (a), which has been obtained from electromagnetic records, seems not to agree with the minimum percentage 53.2 % which has been obtained from electrostatic records. However, this may not be attributed to the change in the waveform characteristics of electromagnetic field changes with the distance of propagation, because Table 2 (b) shows, for example, that the occurrence frequency of the ground discharges each initiated by a cloud discharge does not vary in an appreciable manner between the two ranges of propagation distances corresponding to the whole range of distances of Table 2 (a), i.e., the distances less than 4 km, and the distances lying between 20 and 50 km. Therefore it is not reasonable to think that the difficulty of recording the electromagnetic waveform of a pre-preliminary discharge increases with the increase in propagation distance, and an appreciable part of ground discharges each initiated by a pre-preliminary discharge will likely be recorded as the ground discharges each initiated by a preliminary discharge as the propagation distance increases. Therefore the discrepancy between the percentage obtained from the electromagnetic record and the obtained from the electrostatic record must be attributed to the difference of these two recording methods. In this respect, the electrostatic

Table 2 (a)

Year of the observation	1956	1958	1959	Total
Ground discharge initiated by a preliminary discharge	62.5%	70.7%	76.8%	75.5%
Ground discharge initiated by a cloud discharge	37.5%	29.3%	23.2%	24.5%
Nuber of records *	8	44	237	289

*The distances of discharged are limited roughly within 50 km

Table 2 (b)

Distance	< 4 km	20 - 50 km
Ground discharge initiated by a preliminary discharge	74.5%	76.1%
Ground discharge initiated by a cloud discharge	25.5%	23.9%
Nuber of records	51	96

field-meter covers roughly the frequency range 0 - 1 kc, while the short range waveform recorder covers roughly the frequency range 1 - 100 kc/sec. So that, despite of the great difference in the sensitivity of these two recorders, it will not be unreasonable to consider the existence of a pre-preliminary discharge which is recordable with one of the two recorders but not recordable with the other recorder. If we consider the difference in the frequency characteristics between the two recorders as the most important factor, the pre-preliminary discharge must be considered principally being composed of a discharge which has a duration of the order of 10 ms at least, and which does not produce appreciable radiation pulses with the frequency spectrum, the main part of, which distributes in the range 1 - 100 kc/sec. This means that a pre-preliminary discharge is likely a silent discharge with no-appreciable radiation of pulses with such frequency spectrums and amplitudes that it turns out very difficult to record them with our short range waveform recorder. This condition may be satisfied, if a pre-preliminary discharge might be composed of glow discharges or glow-corona discharges, but it is the problem of the future investigation to clear out this point.

As we have already investigated, the pre-preliminary discharge is a cloud discharge which precedes a ground discharge. Let us consider here whether the pre-preliminary discharge can be

interpreted as the random overlapping of a preceding cloud discharge with an independent ground discharge. The duration T_G of the ground discharge initiated by a pre-preliminary discharge and the duration T_p of the corresponding pre-preliminary discharge were measured on the same electromagnetic waveforms and then a probability distribution of the value $T_p/T_G = C_G$ the normalized duration of a pre-preliminary discharge, have been calculated. Fig. 5 (a) shows the result of this calculation. If it is allowed to replace the probability distribution curve with a straight line indicated in the figure, the statistical mean value of duration of the pre-preliminary discharges will be 0.25*. Table 3 represents the statistical estimation of durations of a lightning discharge obtained from the investigation of the data of CW and

Table 3

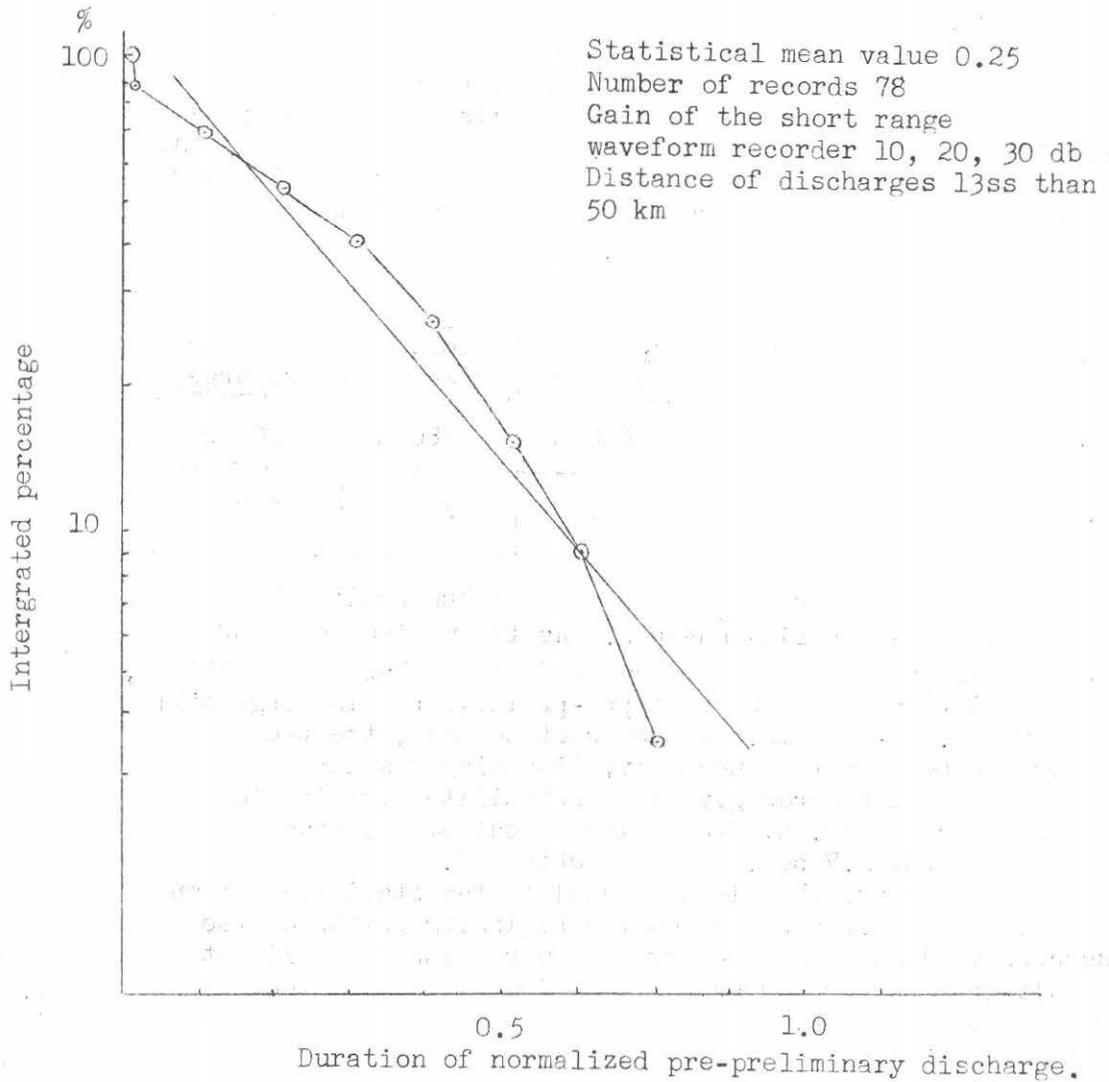
	Ground discharge	Cloud discharge	Lightning discharge
Duration of discharge(*) (Median value)	660 ms	380 ms	480 ms
Number of records	187	1195	328

(*) Statics of records of the lightning luminosity change the data of luminescence changes. As the median value of the ground discharge durations indicated in the Table 3 is 660 ms, the statistical duration of a pre-preliminary discharge will be $660 \times 0.25 = 165$ ms. In contrast to this, the time intervals between two successive lightning discharges measured on CW records give the probability distribution represented in Fig. 5, from which a statistical mean value of about 2.7 sec. is to be obtained.

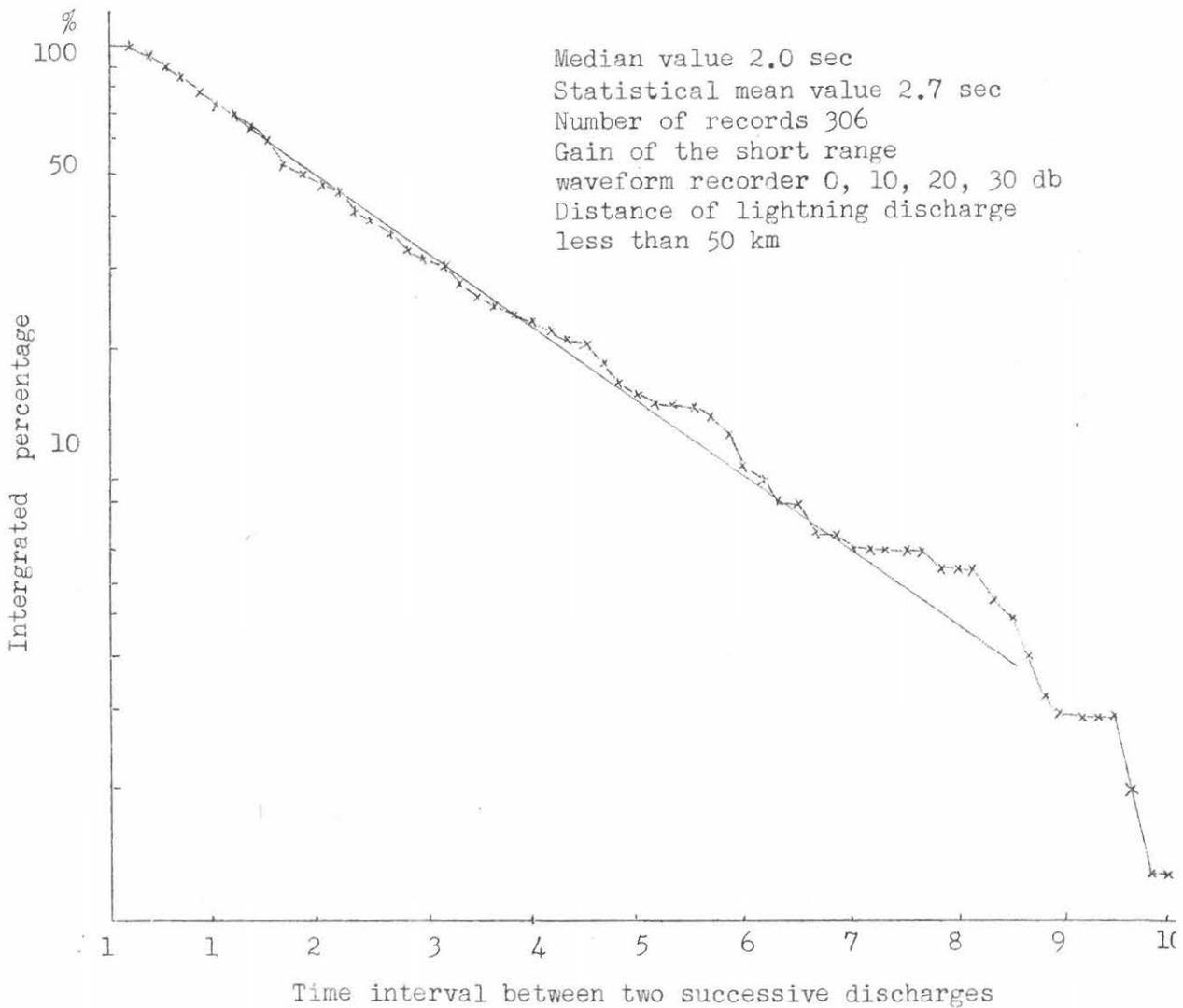
Exactly speaking, this is not equal to the statistical mean of the time intervals between the beginning points of two successive lightning discharges, nevertheless it will not result in a serious error, as the first approximation, to take the above 2.7 sec as a statistical mean of the time intervals in the above sense, because the median value of lightning discharge duration 0.48 sec (see Table 3) is sufficiently shorter than the median value 2.7 sec of the time intervals between two successive lightning discharges (see Fig. 5 (b)). Therefore we can see that the statistical mean of the durations of pre-preliminary discharges differs

* The statistical mean of a probability distribution is given by the reading of the abscissa corresponding to the point, where the reading of the ordinate reduces to 1/e of its initial reading.

Fig. 5



(a) Probability distribution of duration of pre-preliminary discharge.



(b) Probability distribution of time interval between two successive lightning discharges

from that of the time interval between two successive discharge beginnings by the magnitude roughly of one order. This leads to the conclusion that a pre-preliminary discharge is not produced by an accidental partial overlapping of a cloud discharge with a successive but independent discharge, but it is a cloud discharge leading a ground discharge, therefore these two must have a very close causality with respect to the initiation of a ground discharge.

3. Structure of a preliminary discharge

(A) Ignition of a ground discharge

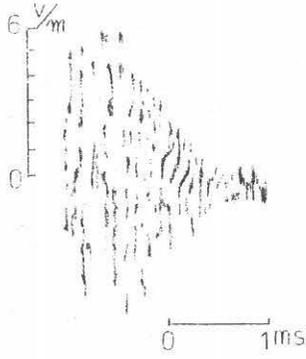
As we have seen in Section 2, at least 53 % of the ground discharges recorded with our field-meter are initiated each by a pre-preliminary discharge. But it will be reasonable to consider that the direct ignition of a discharge is performed by a preliminary discharge in spite of the existence of a pre-preliminary discharge, because there are ground discharges, each of which is not initiated by a pre-preliminary discharge, whereas we can not find any ground discharge lacking a preliminary discharge on the CW records so far obtained. Our investigation further shows that the greater portion of the CW records of a preliminary discharge are each constructed of three sections, Ig, I and L, (see Fig. 2 (a)) or of two sections, Ig and L, except for a few cases which seem to have no Ig section. Therefore we may consider that, the direct ignition of a typical ground discharge is actually performed by the discharge, corresponding to Ig section which will be termed " the igniting discharge " of a ground discharge hereafter.

The photographic investigation of lightning flashes made by Schonland and his colleagues ⁽³⁾ led them to the conclusion that a multiple ground discharge is generally composed of the repetition of a leader return stroke combination, in other words, a ground discharge must be initiated by a stepped leader mechanism. These two electromagnetic and photographic results lead us to the conclusion that a preliminary discharge is nothing other than a stepped leader process or the former includes the latter as a portion of it. ⁽⁴⁾ This point will be touched later on once more. The electromagnetic field changes due to igniting discharges, recorded with the trigger method, can be classified into the following three categories, the examples of which are illustrated in Fig. 6.

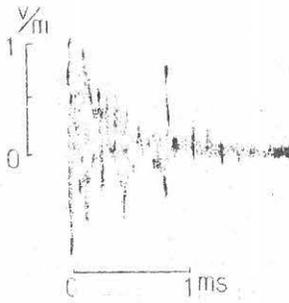
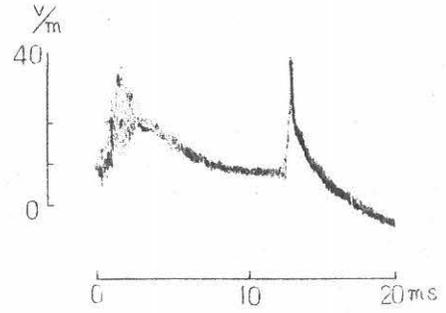
(i) Leader pulse type: Composed of a series of pulses, in which positive large pulses with the differential waveform are repeated at time intervals ranging 50 - 110 micro-sec. In many cases the amplitudes of the pulses reduce gradually from the waveform head to the tail of it, and further, the pulse intervals of more than 110 micro-sec, measured at the waveform head, also reduce towards the tail, where they reach the values roughly ranging 50 - 60 micro-sec. (Fig. 6 (a))

(ii) High frequency type: Composed of a group of small pulses, the repetition frequency of which is not less than 50 kc at least, and which indicates somewhat less clear stepped leader characteristics than the case (i) The amplitude of each pulses forming a group is generally smaller than that

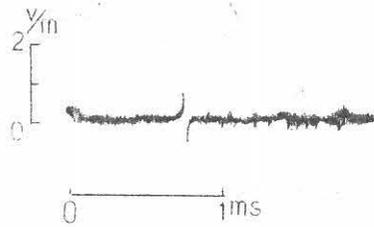
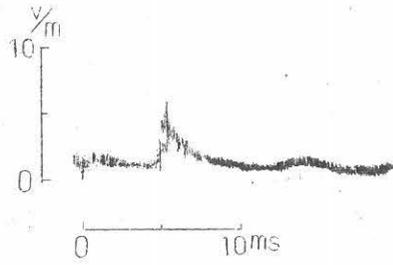
Fig. 6. (1957. 8)



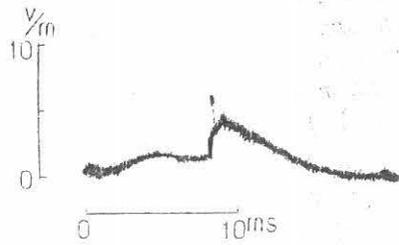
(a)



(b)



(c)



of the case (i).

(iii) Type lacking leader pulses: Small number of minor amplitude pulses with the differential waveform appear at random. The sign of the small pulses is not kept the same throughout the duration of this waveform. (Fig. 6 (c))

These observational facts obtained from the measurement of trigger waveforms lead us to the presumption that many of the ground discharges whose preliminary discharge dose not seem to have a clear Ig section should be regarded to belong to type (iii). The occurrence frequencies of these three types of igniting discharges are represented in Table 4, which indicates that 68 % of the recorded igniting discharges are the leader pulse type and composed of a typical pulse train that indicates the discharge mechanism of a clear stepped leader, 22 % of them are the high frequency type indicating a discharge mechanism with somewhat less clear stepped leader.

Table. 4.

Distance of Discharges	Types of igniting discharges		
	Leader pulse	High frequency pulse	Lacking leader pulse
7 - 12 km.	17	3	2
15 - 60 km.	10	6	2
80 - 150 km.	23	7	4
Total number of waveform records	50	16	8
Percentage	67.6 %	21.6 %	10.8 %

structure and the remaining 10 % are the one without any clear pulse indicating a discharge mechanism other than a stepped leader. Therefore it is evident that the greater part of igniting discharges more or less have a discharge mechanism of just the same characteristics as the typical stepped leader preceding a return stroke. But it must be noticed that there are at least 10 % igniting discharges which have no stepped leader structure. If we exclude the type (iii) out of the category Ig, about 90 % of preliminary discharges must be initiated each a Ig discharge, whereas the remaining 10 % by a L discharge.

We shall next investigate the mechanism of the igniting discharge. If we record the waveforms of electromagnetic field changes due to a ground discharge breaking out at distance roughly less than 10 km, the field change corresponding to the igniting discharge Ig will have the waveform illustrated in Fig. 2 (a), in which the electrostatic component of the

field changes is overlapped with the radiation component composed of a clear pulse train. These records is the figure were obtained with the waveform recorder with a time constant roughly comparable with the duration of an igniting discharge (see Table 14, II 4^A), but if we record the field change due to an Ig discharge with a waveform recorder with a small time constant for example 300 micro-sec, at an appropriate amplifier gain the waveform of the electromagnetic field change will have the structure illustrated in Fig. 7, in which (a) represents a combination of positive radiation pulses with a positive electrostatic field change, and (b)

Fig. 7



a combination of negative radiation pulses with a negative electrostatic field change. The broken line represents the waveform which will be obtained when the waveform recorder has a time constant being long enough in comparison with the duration of an Ig field change. However, the recorder adopted by us has a time constant 300 micro-sec., so the Ig electrostatic field change recorded by our instrument takes the form of an electrostatic pulse, i. e., the waveform illustrated with the full line in the Fig. 7. We shall term this kind of pulses "an ES pulse" hereafter, the actual examples of which are illustrated in Fig. 2 (b). As the polarity of an ES pulse may be inferred to relate to the locally limited vertical movement of electricity which contributes to a small portion of a lightning discharge, so it will be possible statistically to make

clear the movement of the electricity due to a igniting discharge, when we investigate the polarities of ES pulses relating to the Ig discharges appearing in several ranges of distances.

Following this principle we have investigated the relation between the distance of a ground discharge and the polarity of ES pulses corresponding respectively to Ig and L sections on the typical waveform of preliminary discharges, the result of which is summarized in Table 5. According to what the table indicates, the polarity of the ES pulse in the Ig section, and that in the L section, both change their signs from negative to positive with the increase in distances. In fact, the ES pulse polarity in the L section varies from negative to positive, when the distance is increased beyond 4 - 5 km, whereas the ES pulse polarity in the Ig section varies from negative to positive when the distance is increased beyond 7 - 8 km. This indicates that the Ig discharge appears vertically at the higher altitude than that of the L discharge.

Table 5.

Polarity of electrostatic field change		Distance of discharge		
Ig Section	L Section	Less than 5 km.	4 - 8 km.	8 - 20 km.
Negative	Negative	1	0	0
Negative	Positive	14	11	0
Positive	Positive	1	9	17
No change	Positive	10	2	2
No change	No change	2	8	45
Total number of data		28	30	64

The height of an Ig discharge can be estimated from the knowledge about the heights of successive strokes of a multiple ground discharge. Table 6 shows the statistical relation between the

polarity of ES pulses in the Ig section and the distance of the discharge. To obtain this table the ES pulse has been measured on the waveform of a preliminary discharge with a clear Ig section, and the distance of the discharge has been estimated from the knowledge about the relation between the stroke order and the discharging height of each stroke composing a multiple ground discharge, (6); and from the knowledge about the stroke order after which the electrostatic field change due to a leader turns its polarity from positive to negative. As it has already been touched briefly, the table indicates clearly that an electrostatic field change due to a igniting discharge changes its polarity from negative to positive as the distance of a

Table 6.

Polarity of ES puls in Ig Section	Distance of discharges				
	Less than 4 km	5 - 6 km	Round 7 km	10 - 15 km	12 - 25 km
Positive (+)	0 %	0 %	16.7 %	57.5 %	83.3 %
Negative (-)	52.7 %	65.7 %	29.2 %	3.8 %	0 %
Negative followed by positive (±)	15.7 %	12.4 %	4.4 %	0 %	0 %
Polarity can not be determined	31.6 %	21.9 %	50.0 %	38.5 %	16.7 %
Total number of data	19	32	24	26	6

ground discharge increases. Moreover neither a record of positive field change at distances less than 5 - 6 km, nor a record of negative field change at distances larger than 15 km has been found through-out our investigation of the Ig waveforms. Following these observational facts, we may be able to reach the conclusion that an igniting discharge can be replaced with a discharge composed of a vertical dipole inside a thundercloud, the negative electrical charge of which occupies the upper position, and the positive charge of which the lower position. We shall term a dipole with this polarity a negative one. In addition, there is a minority of ES pulses, which have the polarity indicated as "negative followed by positive" in the Table 6. The meaning of this polarity is as follows. When an electrostatic

field change due to a vertical movement of negative electricity is recorded with a field-meter placed inside the field reversal range of the discharge, the record of the field meter will have minimum on it. This point is illustrated by the broken line in Fig. 8. If the field change with a minimum point on it is recorded with a short range waveform recorder with a time constant, for example, 300 micro-sec, it will take the waveform indicated by the full line in the figure, and have the structure of a pulse with a minimum followed by a maximum. This is the ES pulse which we have termed negative followed by positive (\mp) in the Table 6. The table shows that the occurrence frequency of \mp type ES pulse decreases with the increase in the distance of a discharge from the observation station. In spite of our careful investigation of the CW records so far obtained, we could not find any ES pulse of the \mp type. This means that the limiting discharge does not performed by a vertical movement of positive electricity, but by a vertical movement of negative electricity. Therefore we may conclude that the negative vertical dipole discharge performs the role of igniting a ground discharge is produced by the downward movement of negative electricity, i.e., by a negative streamer moving downward. As we have investigated above, about 68% of the igniting discharges recorded by the trigger method are of leader pulse type. To see the structure of this type optically, we investigated many pairs of simultaneous records of a preliminary dischargers, representing the luminosity change and the corresponding electromagnetic field change respectively, and have reached the result that it is by no means difficult to find a pair of records in which the light pulses caught by the luminosity change recorder clearly correspond one by one to the ES pulses as well as to the radiation pulses on the waveform of the electromagnetic field change. Fig. 9 illustrates a typical example of these cases. This correspondence of each light pulse with the respective ES pulse and with the respective radiation pulse

in the Ig section is nothing other than what indicates the

Fig. 9

A pair of simultaneous records of an Ig discharge



Electromagnetic waveform

Luminosity waveform

fact that a leader pulse type igniting discharge must have the structure of a stepped leader.

As it has already been pointed out, a ground discharge usually breaks out between the electricity concentrated at the lower-most part of a negatively charged column n (see Fig. (1.)), and the positive electricity on the earth's surface, so it will be reasonable to consider that a negative vertical dipole which ignites a ground discharge is composed of a negative electrical charge concentration at the lowest portion of the negative column and a positive electrical charge concentration p existing in the minor positive charge distribution round the base of the cloud, because the negative charge of a negative vertical dipole must occupy the upper electrode of it.

Following the results so far obtained, the mechanism of the ignition of a ground discharge will be as follows: At least about 90 % of ground discharges are initiated by an electrical break-down at the lowermost portion of the negative column n , and then a negative streamer which has more or less the structure of a stepped leader runs down from the position of the break-down toward the positive electrical charge concentration p . This is the structure of a typical igniting discharge deduced from the statistical investigation of electromagnetic waveforms.

The igniting discharge thus developed may be expected to cease its progress when the streamer reaches the positive electrical charge p , after which the preliminary discharge will enter either into the I section, a discharge with a slow discharging rate or to the L section, a stepped leader process progressing from p towards the earth's surface according to circumstances.

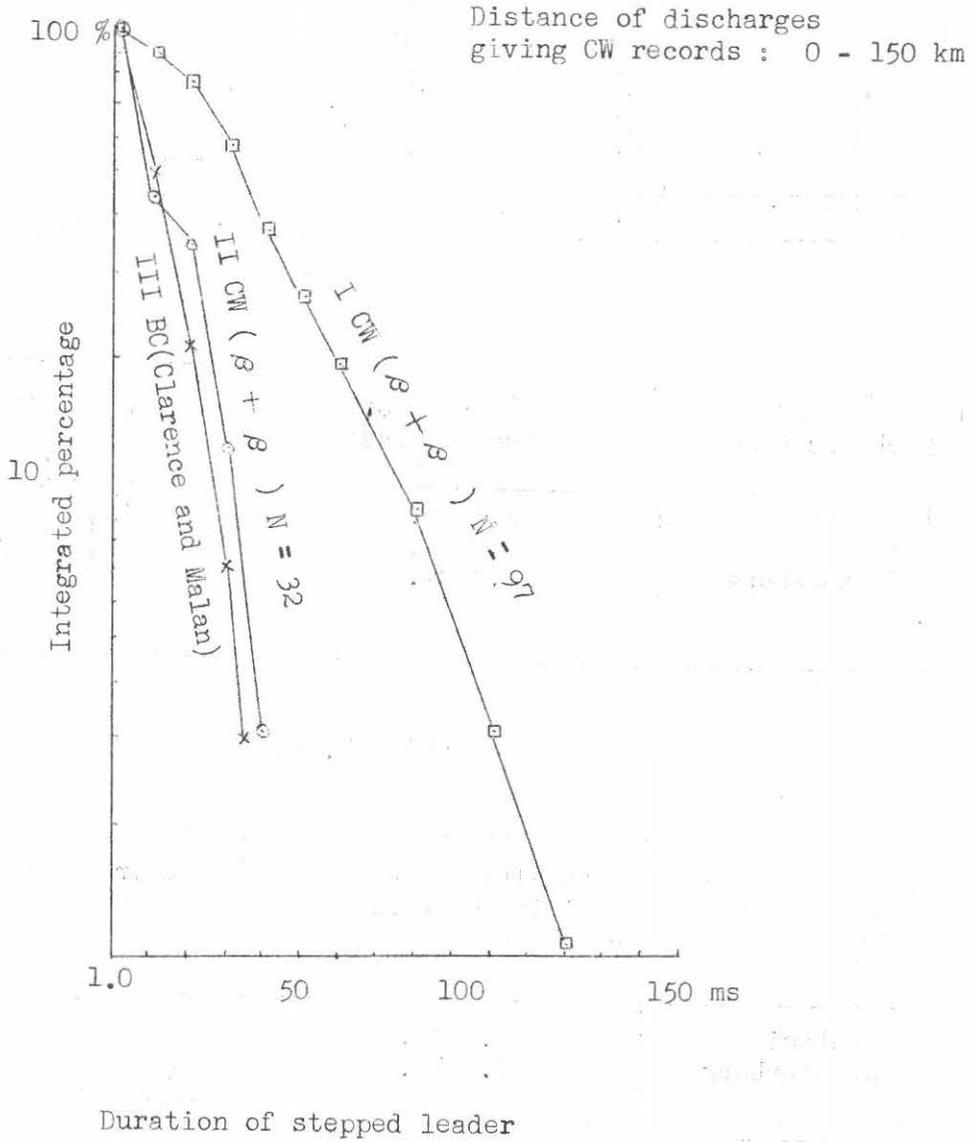
(B) Types of preliminary discharges

The photographic investigation of lightning flashes made by Schonland and his comrades (3, 11) indicated the existence of two categories of stepped leaders, i.e., α type which does not change its characteristics throughout the period of progression, and β type which changes its characteristics when the leader passes through a space charge existing closed beneath the base of a thundercloud. According to what we have touched briefly in the previous paragraph (A), the preliminary discharge of a ground discharge should be inferred to have a close relation with the process of a stepped leader. Therefore the electromagnetic waveforms of preliminary discharges should be expected being classifiable into these two categories. As described in the Paragraph (A) about 90% of the recorded waveforms of preliminary discharges each are constructed either of Ig, I and L sections or of Ig and L sections, and the remaining 10 % of them, seem to be composed only of L section. It will be reasonable to infer that a preliminary discharge is developed actually by the α or $\alpha\beta$ type stepped leader process, when the electromagnetic waveform of it has no I section and the transition from Ig to L is so smooth that a definite boundary can hardly be drawn between these two (α , or $\alpha\beta$, type), or when the waveform is composed only of L section (α type). As for the β type, the waveform of a preliminary discharge must change its characteristics on half way of it rather abruptly and clearly, moreover it should not have any measurable section intermediate characteristics, if we attempt to let the β type preliminary discharge defined from the nature of electromagnetic waveforms exactly to correspond to the β type stepped leader investigated with the photographic method. The reason of this is that the Boys' camera photograph of a β type stepped leader generally does not indicate any pause of the leader progression existing at its transitional point. Therefore, if the electromagnetic waveform of a preliminary discharge has no measurable I section, and the differences in characteristics between Ig and L sections are remarkable, and moreover, the transition from Ig to L is considerably abrupt that it is possible to draw a boundary between these two, then the preliminary discharge may be regarded exactly to correspond to a β type stepped leader. But, if we attach a great importance to the point that the change in characteristics from Ig to L must be clear, a preliminary discharge producing a waveform composed of Ig, I and L sections must be regarded as to correspond to a variation of the β type stepped leader, provided the differences in characteristics between Ig and L sections being appreciable. Let us term this type preliminary discharge as the

β type,* even through an appreciable portion of the preliminary discharges included in this category might be of very different nature from the photographic conception of the β type stepped leader. Fig. 10 prerepresents three probability distributions of stepped leader durations: Curve (I) represents the case of β type preliminary discharge duration T_{IgL} (time length from the beginning of Ig to the end of measured on the CW record mixed with β' type preliminary discharge duration T_{IgIL} , Curve (II) the case of α or $\alpha\beta$ type preliminary discharge duration T_{IgL} mixed with α type preliminary discharge duration T_L (the case of the waveforms Laking Ig section), and Curve (III) the result of the photographic measurement (4) of stepped leader durations including both α and β types. The agreement of the Curve (II) with the Curve (III) indicated in the figure is fairly well, and the situation is not changed even when we consider the distribution of β type preliminary discharge duration T_{IgL} instead of the Curve (II). This means that the probability distribution of duration of preliminary discharges which lack I or Ig section is practically identical with that of stepped leaders measured on Boys' camera photographs, in other words, a stepped leader caught by the photographic method must correspond either to a IgL type preliminary discharge, or to a L type preliminary discharge, or accordingly to the L section of a $IgIL$ type preliminary discharge. The disagreement between the Curve (I) and the Curve (III) must, therefore, be attributed to the influence of $IgIL$ type, i.e., β' type preliminary discharges, because the Curve (III) is concerned with the preliminary discharges which lack at least I section whereas the Curve (I) includes the preliminary discharges composed of the three sections Ig, I and L. To know the occurrence frequency of these two types of stepped leaders, we investigated year by year the recorded percentages of the two types on the trigger waveforms of ground discharges, the result of which is represented in the Table 7. The table indicates that the occurrence frequency of β type stepped leader in the wider sense is 5 - 9 time larger than that of α type stepped leader. This will be one of the most important reasons, why a Boys' camera photograph indicating the fine structure of a stepped leader process has not been obtained in our country till to the present. Another reason why a Boy's camera photograph indicating clear steppings in the upper-end portion of a lightning channel, from where the Ig section of the waveform of a preliminary discharge likely originates, (see Fig. 9) could not be recorded in our country, seems to depend on the altitude of a thundercloud base relative to that of the positive electrical charge concentration p contributing

* In practice most of the $IgIL$ type preliminary discharges recorded by us are to be classified into the category of β' type.

Fig. 10



to lg discharge.

Table 7.

Year of the observation	Types of stepped leader			Number of data
	α type	β or β' type	type	
1956	11.8 %	58.8 %	29.4 %	17
1957	8.3 %	77.0 %	14.7 %	156
Total	8.7 %	75.1 %	16.2 %	173

Table 8 (a)

Place of the observation	Mean altitude of thundercloud base	Number of the data
Maebasi	1.1 km.	14
Kew	1.0 km.	18 (1)
Johanesburg	2.1 km.	10 (3, 6)

Table 8. (b)

Place of the observation	Mean altitude of a positive electrical charge p	Number of data
Meabasi	2.3 km.*	19
Johanesburg	1.4 km.	11 (6)

* See Table 16

Table 8. (a) and (b) represent the results of estimation of mean altitude of thundercloud base and those of mean altitude of positive electrical charge concentration p at a few places in the world. The data at Kew in England have been obtained from

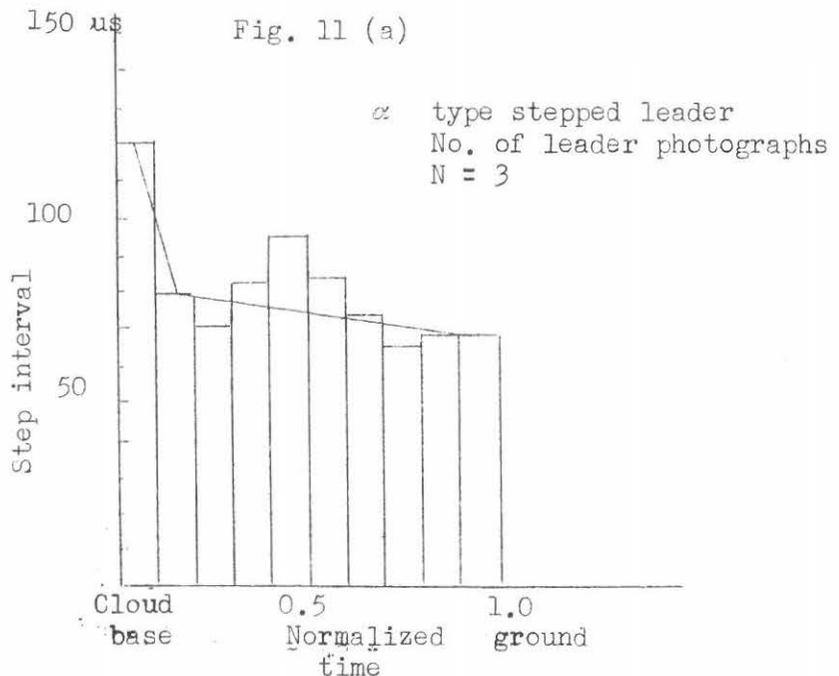
Simpson's altielectrographic measurement of thunderclouds(1). and the data at Johannesburg in South Africa are referred to the photographic measurement of lightning flashes made by Schonland and his colleagues (3, 6). The altitude of a thundercloud base at Maebasi in our country was measured with balloon and telescope method by the staffs of the Maebasi Meteorological Observatory and the data in the table were kindly offered to us. The Maebasi data given in the table 8 (b) is referred to the result which will be obtained through the discussions in the Section 4, A. Table (a) combined with Table (b) clearly indicates the point that the relation between the altitude of a thundercloud base and that of positive electrical charge p is just reversed between Maebasi and Johannesburg, even though we consider the differences in the method of measurements between Maebasi and Johannesburg, which resulted in the table (b). At Maebasi, the altitude of a thundercloud base is generally lower than that of the positive electrical charge center p, so that it will be very difficult in this district to photograph the β portion of a β type stepped leader, which must be inferred to take place between the lowermost part of the negative column and the positive electrical charge center p in a thundercloud (see Fig. 1). At Johannesburg, however, the altitude of a thundercloud base is usually higher than that of positive electrical charge center p, so that it will be in no way difficult, even if not easy, to obtain such a β type stepped leader photograph. These two reasons combined with a high humid climate in summer in the Maebasi district, which will limit the visibility range and with the minority of thunderstorm days in our country probably make it very difficult to obtain a photograph of the α type stepped leader indicating clear step processes.

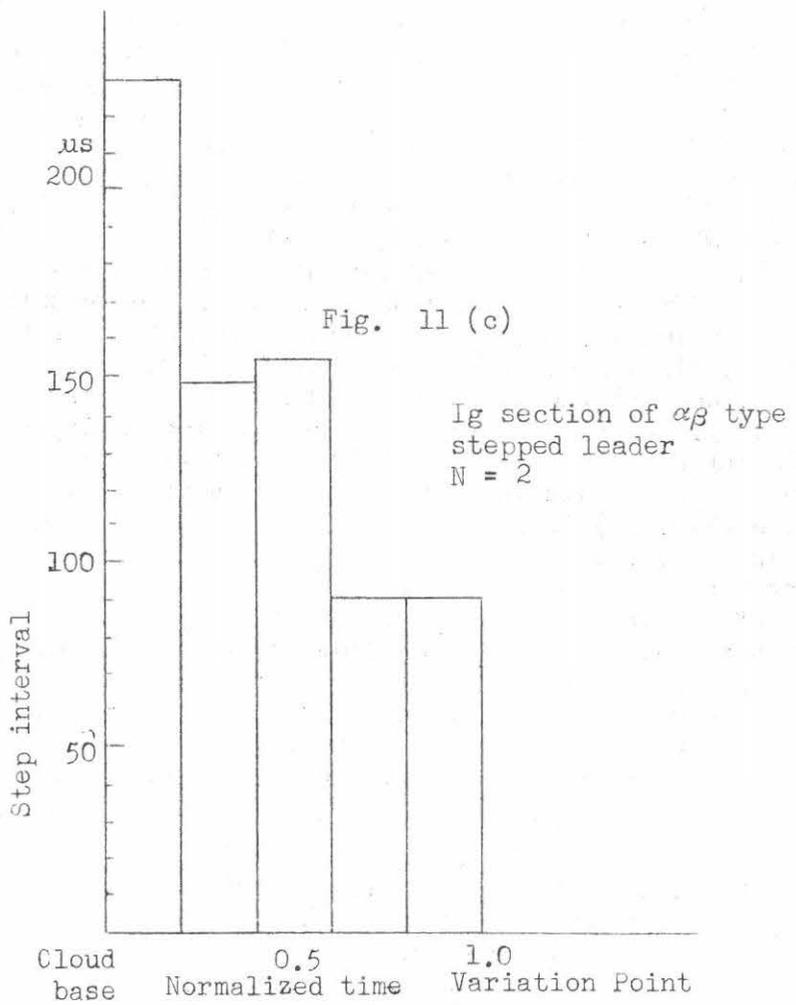
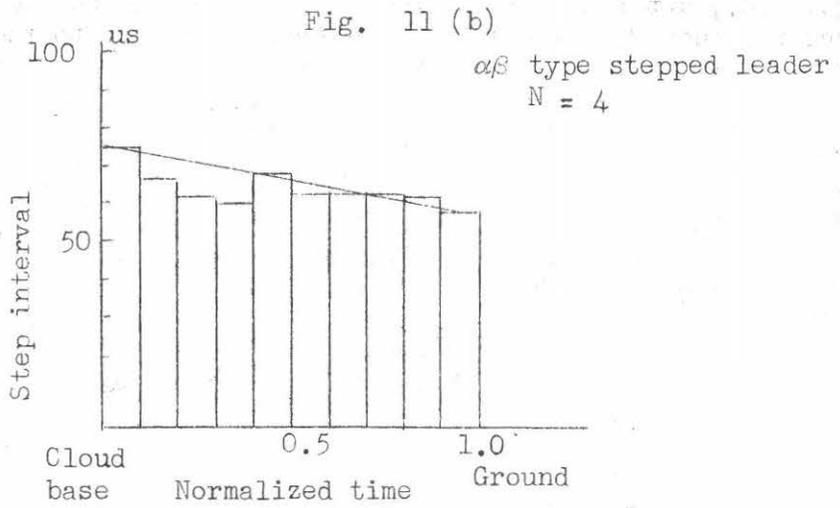
(c) Pulsive structure of the electromagnetic waveform of a preliminary discharge

As we have already investigated, if we succeed to record simultaneously the electromagnetic field change and the lightning luminosity change due to the Ig portion of a preliminary discharge under a very favorable condition it is easy to find the one by one correspondence existing between the electromagnetic radiation pulse and the light pulse (see Fig. 9 II 2(A)). Concerning this point Schonland (7) reported that the average time interval between electromagnetic pulsations of the preliminary field changes agrees fairly well with the average of the photographically measured intervals between steps of a first leader.

To see this point more comprehensive, the time intervals between steps have been measured on few stepped leader photographs recorded by us together with those obtained at Socorro in the United States in 1958 and kindly offered to us from Dr. Kitagawa. Next, the time length needed for a stepped leader to progress from a cloud base to the earth was measured on a moving photograph along the trunk of a ground stroke and divided into ten sections. Then the step time intervals involved in each of these ten sections have been averaged section by section. The variation characteristics of step intervals with the progress of a stepped leader have been obtained on each stepped leader photograph in this way.

The variation characteristics of step intervals thus obtained for each leader have been averaged between the leaders of the same category, the result of which is represented in Fig. 11 (a) and (b). In the figure, (a) represents the case of α type stepped leader and (b) the case of $\alpha\beta$ type stepped leader - an intermediate one between α type and β type. In the case of β type stepped leader it is very difficult to measure exact time intervals





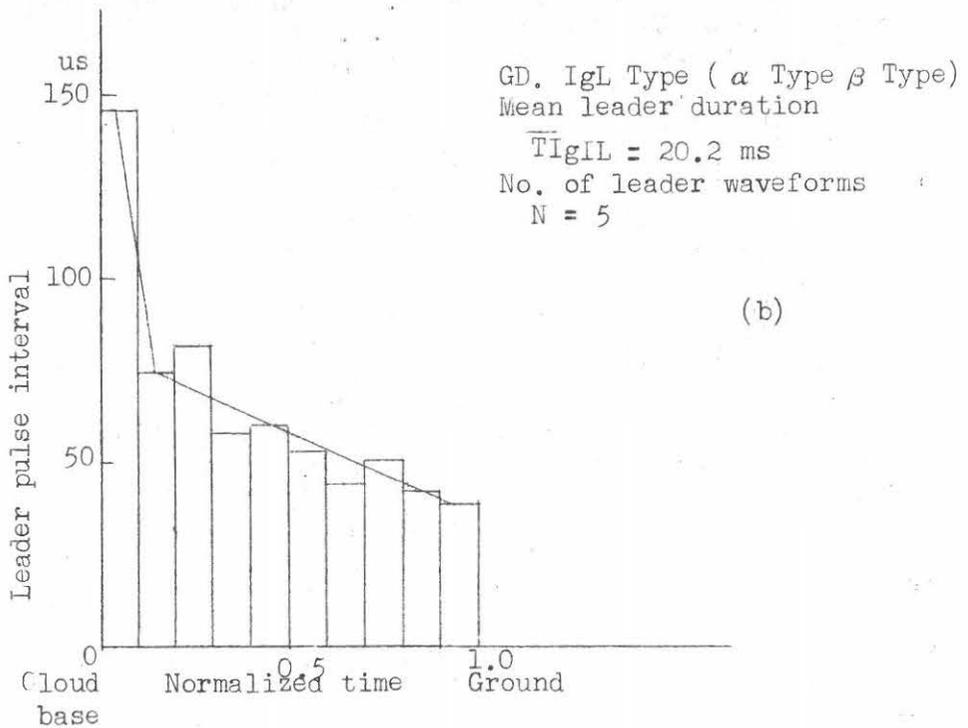
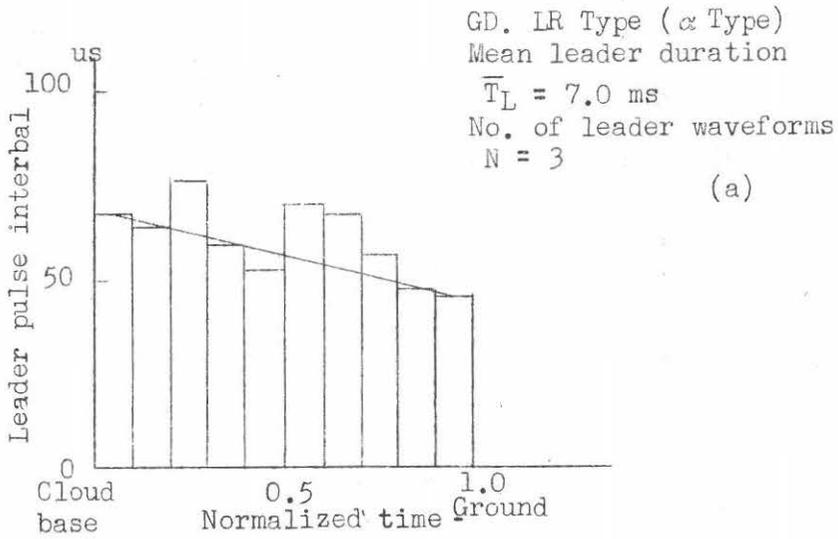
between steps in the later half section of the photographic image, i.e., after the occurrence of variation in the leader structure, therefore the time length corresponding to the distance between the cloud base and the variation point of the structure was divided into 5 sections. The variation of step intervals with the leader progress in the initial portion of it has been measured in the same way as before, the result of which is represented in Fig. 11 (c). It is very clear that the step intervals generally become smaller and approach to a normal value*, roughly 70 micro-sec., as the leader advances from the cloud base to the ground, and this tendency is not changed from a leader type to another. Therefore the step time intervals in the portion of a stepped leader close to the cloud base are generally larger than the normal value, and it is not seldom that they actually exceed 100 micro-sec., which seems to indicate that a stepped leader has its step intervals prolonged when it take place inside a thundercloud. However, when the leader once steps out of the thundercloud and travels the clear space between cloud and ground, the intervals reduce to a normal value round 70 micro-sec. For the sake of comparison, the time duration of a preliminary discharge was measured on the electromagnetic waveform of a ground discharge, and divided into ten sections. Then the time interval between successive radiation pulses of appreciable amplitudes occurring in each section were averaged section by section. The variation characteristics of the intervals between these appreciable pulses with the progress of a preliminary discharge has been averaged between the same type preliminary discharges. The result is indicated in Fig. 12, in which (a) represent the L type preliminary discharge, (b) the IgL type preliminary discharge, and (c) the IgIl type preliminary discharge respectively. We can clearly see that the manner in which the time intervals between radiation pulses with appreciable amplitudes varies with the development of a preliminary discharge (Fig. 12) is just the same as that of the step intervals (Fig. 11).

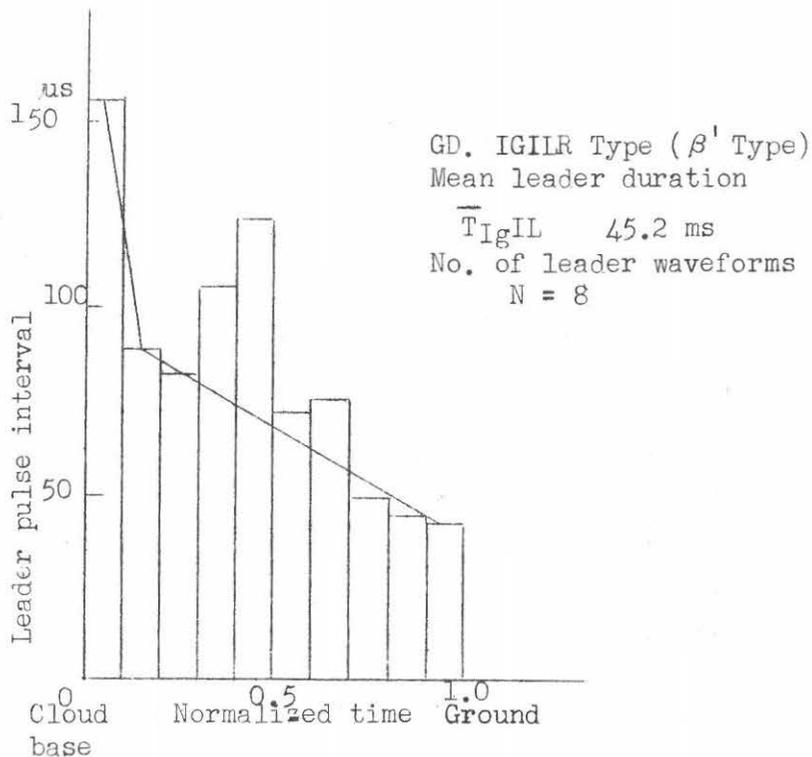
In great many cases the pulse intervals in the initial portion of the Ig section of preliminary discharge usually have the values ranging from 100 to 150 micro-sec., which seems to correspond fairly well with the step intervals occurring in the portion of a stepped leader near to the cloud base quantitatively.

But the normal radiation pulse intervals appearing in the later L section of the preliminary discharge are seen to

* The median value of the step time intervals measured on all our stepped leader photographs. The average value of same data is roughly 50 micro-sec.

Fig. 12





take the values 40 - 50 micro-sec. which is smaller than the normal value of the former case, i.e., the value obtained with the photographic method. This point will be touched later once more. The increase in pulse intervals existing in the middle portion of the leader duration (Fig. 12 (c)) corresponds to the I section, in which it is rather difficult to measure pulse intervals, because the section usually involves many unmeasurable small amplitude pulsations except for small number of narrowly measurable ones.

According to what we have investigated in the previous paragraph (B), it is clear that the three types of preliminary discharges must have a close correspondence with the three types of stepped leaders.

This point has been summarized in the Table 9. Following the above idea, (a), (b) and (c) of Fig. 12 should be inferred to correspond to the case of α type stepped leader, the case of β type stepped leader mixed with α type stepped leader, and the case of β' type stepped leader respectively. From this it follows that the step intervals of a β type leader along the trunk of the leader statistically tend to attain the normal value toward, the end of the leader advance, and it seems that no appreciable differences exist between the L section of an α type leader

Table 9.

Types of preliminary discharges		Types of stepped leaders
IgIL type (Leader composed of three sections Ig, I and L)		β' type (β type with long duration)
IgI type (Leader lacking I)	With a sharp transition from Ig to L	β type
	With a intermediate transition from Ig to L	$\alpha\beta$ type
	With a gradual transition from Ig to L	α type
L type (Leader lacking Ig and L)		α type

(Fig. 12 (a)) and that of a β' type leader, (Fig. 12 (c)). This point will be touched once more in the following discussion. The above result combined with the evidence, already obtained from the photographic investigation of the stepped leaders, seems to lead us to the conclusion that statistically no appreciable difference is existing between the step structure of α type leaders and that of β type leaders so far as the step intervals being concerned. So that the principal reason, why the step structure of a β type stepped leader can not clearly be photographed with a flash resolving camera once after the variation of the step structure having been occurred, should not be sought in the increase in the frequency of step streamer repetition, but it must be attributed to the decrease in the brightness of each step streamer, i.e., to the decrease in the intensity of luminosity pulsations. Moreover difficulty to photograph the step structure of a β type leader after the variation of the structure may be enhanced by the decrease in each step length.

To identify quantitatively the step intervals with the radiation pulse intervals from a statistical stand point of view, the probability distributions of the step intervals in the three types of stepped leaders have been calculated. The results are represented in Fig. 13, in which (a) is concerned with L section and probably corresponds to α type stepped leaders, and (b) with Ig section and corresponds to the initial portion of stepped leaders. In Fig. 13 (a),

Fig. 13 (a)

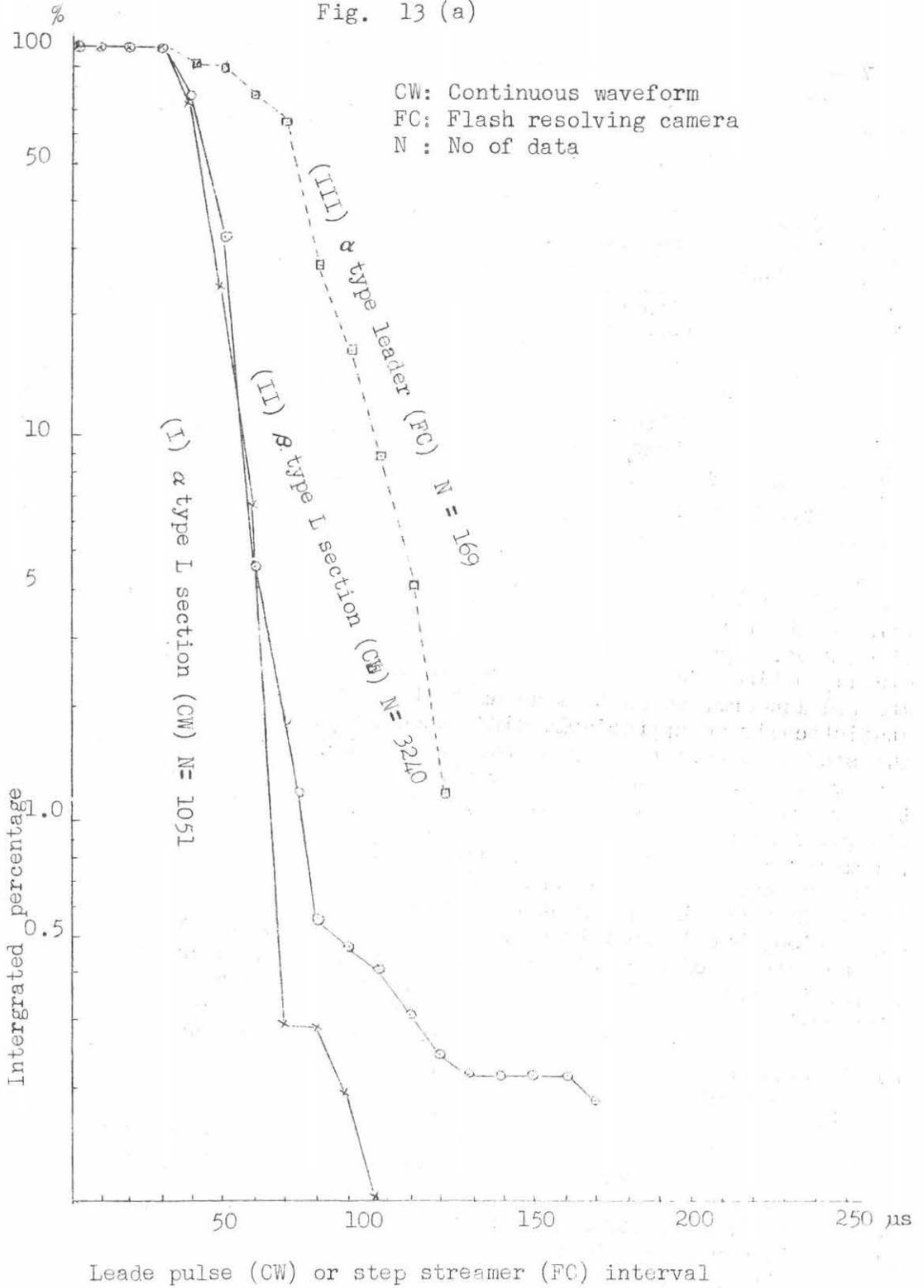
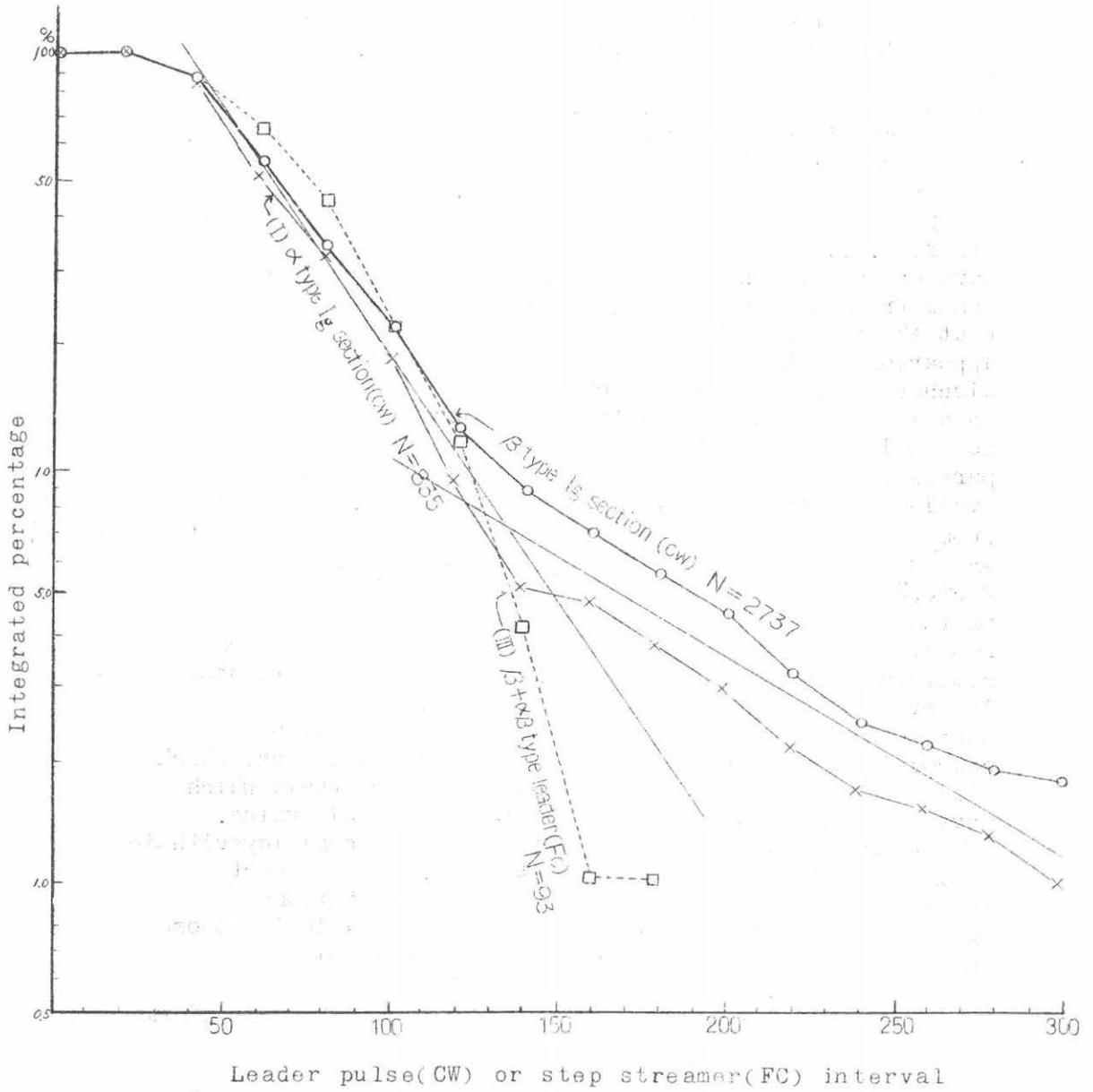


Fig. 13 (b)



the distributions (I) and (II) are obtained both from the data of short range atmospheric waveforms, and the distribution (III) from the data of flash photographs. The distribution (I) represents the radiation pulse intervals in the L section of α type preliminary discharges, and (II) the pulse intervals in the L section of β type preliminary discharges. The fairly well coincidence between these two distributions (I) and (II) shows that any appreciable statistical difference in the step intervals can not be found between the L section of an α type leader and that of a β type leader. This is just the same conclusion as that already obtained in the previous discussion. The distribution III represents, on the other hand, the case of the photographic record of α type stepped leader. As the figure indicates, Curve (I) or (II) and Curve (III) may be considered being roughly parallel with each other. This parallelism indicates that the probability of occurrence of a radiation pulse interval value and that of occurrence of a step interval value is identical with each other, i.e., the radiation pulse on the electromagnetic waveform and the step structure on the photographic record comes from the same origin. Therefore it must be concluded that the radiation pulses with appreciable amplitudes appearing in the preliminary discharge portion of a ground discharge must each correspond to a step streamer involved in a stepped leader. The fact that Curve (I) or (II) does not fully coincide with Curve (III) in spite of their parallelism seems to come from the shortage of the available photographic record of the leaders, as well as from the procedure of selecting of the photographic record which are suited for the step interval measurements. These factors combined with relatively lower time resolving power of the flash resolving camera in comparison with the time resolving power of the short range atmospheric waveform recorded with a fast time sweep, tend to limit small step intervals being measured on the photographic record, therefore the step interval probability distribution calculated from the photographic data must be the one which will be obtained by neglecting those step intervals which have the smaller values than a certain threshold value. If the probability distribution plotted on a semi-logarithmic scale takes the form of a straight line, we can expect theoretically a parallelism of the two distributions, one including all step intervals, the other excluding those intervals which have smaller value than a certain threshold value. The probability distribution of radiation pulse intervals in the Lg section of a preliminary discharge are represented by Curves (I) of Fig. 13 (b), in which Curve (I) corresponds to the case of α type preliminary discharge and Curve (II) to the case of β type. The coincidence of these two Curves (I) and (II) is fairly

well, which indicates no appreciable differences existing in the Ig section between α type and β type, so far as the radiation pulse intervals being concerned. Relating Curves (I) and (II), we can separate two groups of radiation pulse intervals, i.e., the minority group with long pulse intervals, the statistical mean value of which is 94 micro-sec. and the majority group with short pulse intervals, the statistical mean value of which is 42 micro-sec. If we compare these two groups, which are involved in the Ig sections of the leader waveforms, with the step interval distribution in the initial section of β type leaders represented in Fig. 11 (c), we can conclude that the minority group with long pulse intervals correspond to the initial portion of a Ig section, and the majority group to the later half portion of it.

The step interval probability distribution obtained from the data of flash photographs, on the other hand, is represented by Curve (III) of the same figure. As Curve (III) is concerned with the initial portion of a β type or $\alpha\beta$ type stepped leader, it is natural that the distribution (III) really coincides with the distribution (I) and (II), however, the coincidence is limited only to the portion of the distribution corresponding to the majority group and the portion of the minority group is absent in the distribution (III). This probably means that the minority group representing long step intervals usually present themselves in the initial portion of a stepped leader to ground, so that the group will almost always be hidden inside the thundercloud and hardly be caught by the flash resolving camera.

We have hitherto discussed the radiation pulse intervals with appreciable amplitudes, i.e., the pulses each radiated by a step streamer, and not touched on the small pulsations with rather high repetition frequencies superposed on the series of step streamer pulsations. These small pulsations appearing on the electromagnetic waveform of a stepped leader generally increase its amplitude toward the end of the leader, and become very predominant especially after the leader discharge having entered into the L section. (see Fig. 2 (a), (c)) As it was described in one(8) of our previous reports, the measurement of the frequency of these small pulse repetitions on the trigger waveform with 2 ms time sweep gives the value roughly amounting to 50 kc or more. This kind of small pulsations can, however, also be found on many waveforms of the dart leaders preceding the succeeding return strokes, or be found in association with some of the predominant pulses involved in cloud discharge waveforms, or being involved in a after discharge following to a return stroke. As the discharge mechanism relating to these latter three cases does not seem to possess a large scale stepwise structure, so the small pulsations appearing on the waveform of a stepped leader must not come from a large scale stepwise

process of the leader discharge. Therefore these small pulsations with high frequency of repetition generally may be attributed random secondary small streamers - so to speak they would be a kind of corona streamers - supposedly occurring around the head portion of a completed return stroke.

Relating to the propagation characteristics of leader electromagnetic waveforms, we have investigated the variation in the duration of Ig11 type preliminary discharge waveform with the distance of propagation. The results obtained are summarized in the Table 10, in which the propagation distances have been estimated from the gain of the recorder with which

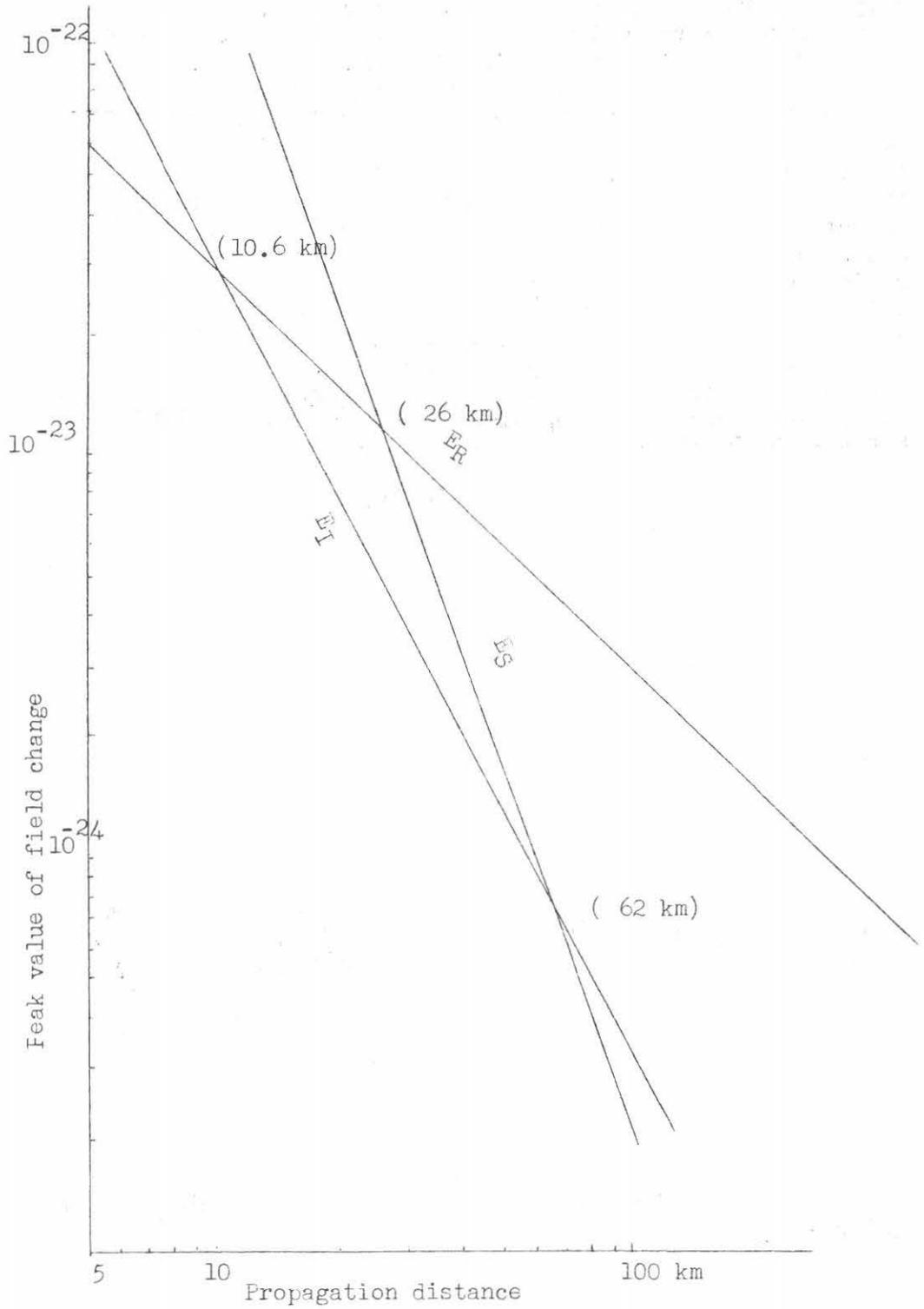
Table 10.

Distance of propagation	Duration of Ig11 type preliminary discharge waveforms* (Median)	Number of data
Less than 30 km.	46.9 ms	29
30 - 60 km.	30.9 ms	25
100 - 300 km.	24.0 ms	43
300 - 1000 km.	6.7 ms	14

* The waveforms were recorded with the recorder with the time constant 300 micro-sec. and adjusted at gain 20 or 30 db.

the waveforms were recorded, and from the structural variation of the waveforms with propagation distances so that they have a statistical meaning. It is clear that the durations of preliminary discharge waveforms generally reduce their magnitude with the increase in their propagation distances. If we assume the electric current waveform of a ground stroke given by Morrison⁽⁹⁾ to be a probable one, it is easy to know the variation, with the propagation distances, of the relative peak values of the three components of the electromagnetic field changes due to a ground stroke, i.e., the electrostatic component E_S , the induction component E_I and the radiation component E_R . The result of calculation of the peak field changes is represented in Fig. 14, in which the ordinate is represented in an arbitrary unit. It is clear that $E_R = E_I$ occurs at the distance 10.6 km., while $E_R = E_S$ occurs at the distance 26 km. These distances will be reduced, if we assume a current waveform of more narrow pulse width. As the waveforms of individual leader pulses have usually a more narrow pulse width than those of ground

Fig. 14



strokes,* it will be reasonable to assume, that within the range of distances less than 30 km. the electrostatic component of the preliminary field changes over-takes the other components and in the range larger than 100 km. the electromagnetic radiation icomponent predominates. Therefore the reduction of leader duration from 46.9 ms to 30.9 ms in median values may be caused by the attenuation of electrostatic component of electromagnetic field changes due to a stepped leader involved in a ground discharge, the reduction from 30.9 ms to 24.6 ms indicated in the table may be attributed to the attenuation of electromagnetic induction component, and the reduction from 24.6 ms to 6.7 ms seems to be attributed to the attenuation of electromagnetic radiation component. A typical example of the waveform originating from a ground discharge in the range of distance 300 - 1000 km is reproduced in Fig. 15. The disturbances in the preliminary section of the waveform, probably corresponding to a part of a stepped leader, are seen not to continue till to the begining of the following return stroke, but to vanish on half way to it.

Fig. 15.



*The mean value of the leader pulse width obtained by us is 26 micro-sec., while that of the ground stroke gives 100 micro-sec.

According to our statistical measurement of the waveform of a preliminary discharge recorded within the range of distances 0 - 60 km the duration of L section T_L of a ground discharge has the median value 14 ms. So the duration 6.7 ms of the preliminary disturbance duration indicated in the Table 10 must statistically be included in the L section of a preliminary discharge. As we have already investigated, the large leader pulses in the L section of a preliminary discharge are usually distributed rather uniform throughout the section, so it will not exactly be correct to attempt to find the origin of the preliminary disturbances on the waveform like that illustrated in Fig. 15 in the large amplitude leader pulsations corresponding to step streamers. No sufficient reason seems to exist why the leader pulses included in a particular portion of the L section of a preliminary discharge really contribute to forming up of the preliminary disturbances after they have traveled a long distance, and why the other portion of the L section, especially the final portion at least, attenuate actually to a complete degree. Therefore the complex structure of the L section, i.e., small random pulsations being superposed on a somewhat regular series of appreciable leader pulses, must be the cause of forming up the preliminary disturbances, an exact interpretation of which, however, will be a problem of future investigations.

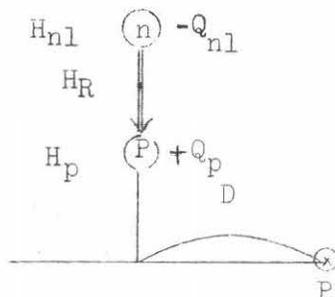
Concerning the Ig section, the median value of the preliminary discharge durations does not reduce to a value smaller than 24.0 ms, so long as the distances of their propagation do not exceed roughly 300 km, and it is clearly large than 14.0 ms, the median value of the L section of the discharge. Therefore it is very evident that the leader pulses included in the Ig section of the discharge are attenuated thoroughly when they propagate the distances roughly beyond 300 km, whereas at nearer distances less than 300 km, the attenuation of them is by no means so serious.

4. The altitude of the electrical charge center contributing to a ground stroke

(A) The altitude of the first ground stroke

As we have already investigated in the previous section, the first ground stroke must be inferred generally being initiated with the discharge of a negative dipole like that illustrated in the Fig. 16. If we assume that the dipole is composed of a negative electricity $-Q_{n1}$ concentrated at an altitude H_{n1} , and a positive electricity Q_p concentrated at an altitude H_p , and that the horizontal distance of the discharging point from the observation station is D , the discharge of the negative dipole will be replaced by the movement of a negative electricity $-Q_{n1}$ traveling downwards from the altitude H_{n1} to H_p . Further, if we record the electrostatic field change caused by this negative dipole discharge at several different horizontal distances from it with the short range waveform recorder, the variation of the polarity of a ES pulse due to the dipole discharge.

Fig. 16.



$$H_R = D_R / 2^{\frac{1}{2}}$$

$$D_R = (H_p H_{n1})^{1/3} (H_p^{2/3} + H_{n1}^{2/3})^{\frac{1}{2}}$$

Electrostatic field reversal distance

with the distance of its propagation is expected theoretically to have the statistical features represented in the Table 11.

Table 11.

Polarity of ES pulse in the Ig section	Distance of discharges		
	$D \leq \sqrt{2H_R} *$	$\sqrt{2H_R} \sim \sqrt{2H_-}$	$\sqrt{2H_-} \leq D$
+	0 %	0 %	100 %
-	100 %	0 %	0 %
\mp	0 %	100 %	0 %
Number of data	100	100	100

$$* \sqrt{2H_R} = (H_p H_{n1})^{1/3} (H_p^2 + H_{n1}^2)^{1/2} \quad \text{Field reversal distance}$$

It is easy to see that the theoretical statistics indicated in the Table 11 are roughly identical with the observational results represented in the Table 6. As the Table 11 assumes the discharge of a negative vertical dipole fixed at a certain altitude and considers the observations of electrostatic field changes at several different distances from the dipole, so it will be natural that the coincidence in details of the two tables is in no way satisfactory.

In actual ground discharges, the altitudes H_p and H_{n1} , at least, must be considered to change their values from a discharge to another, therefore the theoretical statistics of dipole discharges must take this point into account. As the altitude of a vertical dipole is determined if we give the two altitude values H_R and H_{n1} (see Fig. 16), so the altitudes of the vertical dipoles composing a statistical group of Ig discharges can be arranged in series of altitude values (H_R^1, H_{n1}^1) , (H_R^2, H_{n1}^2) , (H_R^3, H_{n1}^3) in order of H_{n1} values.

For the sake of simplicity, let us assume that the probability of occurrence of a vertical dipole at various altitudes is every where equal, and in no cases the probability corresponding to a certain altitude becomes larger than that corresponding to another. Next we shall consider a vertical distribution of these dipoles each with an equal probability of occurrence. If the number of the observed data were very large, it would be better to assume a continuous distribution of dipoles.

However, we shall assume here that H_{Ri} as well as H_{ni}^i distribute at an equal interval, and the relation $H_{ni}^i = H_R^i$ is satisfied, that is, a group of vertical dipoles, which satisfy the conditions $\frac{H_{ni}^j}{H_R^j} = \text{const.}$ ($j = 1, 2, 3, \dots$), distribute at equal distances given by $\frac{H_{ni}^i}{H_R^i} / (i-1)$. If the

electrostatic field change due to the discharge of one of this dipole group are recorded at several distances from the dipole, the statistical feature of polarity variation of the field change with the observation distance must be inferred to be given by the Table 11. The same statistics relating to the group of dipoles, therefore, must be represented by a superposition of the statistics of the individual dipole. Table 12 represents the result of statistics concerned with the dipole group, which is composed of 10 elements to let the result represented in the Table 12 to approach to that of the Table 6. The agreement of the result of the Table 12 with that of the Table 6 may be regarded as being fairly well, so long as we consider the point

Table 12.

Altitude = $D/2$ *		H_R^1	H_R^2	H_R^3	H_R^4	H_R^5	H_R^6	H_R^7	H_R^8	H_R^9	H_R^{10}					
		H_n^1	H_n^2	H_n^3	H_n^4	H_n^5	H_n^6	H_n^7	H_n^8	H_n^9	H_n^{10}					
Polarity of ES pulse	+	0	0	0	0	10	20	30	40	50	60	70	80	90	100	%
	-	100	90	80	70	60	50	40	30	20	10	0	0	0	0	%
	\mp	0	10	20	30	30	30	30	30	30	30	30	20	10	0	%
Number of data		100	"	"	"	"	"	"	"	"	"	"	"	"	"	"
Boundary distance		$D_+/\sqrt{2}$				$D_+/\sqrt{2}$						$D_-/\sqrt{2}$			$D_{\mp}/\sqrt{2}$	

* D = Distance of discharge from the observation station

that an appreciable portion of the waveforms giving the results of the Table 6 were not recorded at adequate gains to determine the polarity of a ES pulse in the Ig section of a waveform and they result in the large percentages, at all distances, of the category represented in the fourth row of the Table 6, i.e., the case in which the ES pulse polarity could not be determined. The value 30% in the third row relating to the \mp polarity of the Table 12 can be reduced to a value round 20% through the reduction of the overlapping between two successive dipoles. This means that the lengths of individual dipoles must sufficiently be small compared with the distribution range of all the vertical dipoles constructing the statistical group. Using the results indicated in the Table 12, we can determine the boundary distance D_+ , D_- , D_{\mp} ,

D 2, which represent the distances at which the statistical percentage values represented in the respective row +, -, 1 in the table increase from 0 % to 10 % or, vice versa, decrease from 10 % to 0 %, the result of which is indicated in the last row of the table. It is easy to show that these boundary distances relate to H_R , H_{nl} as follows:

$$D_{+} / \sqrt{2} \doteq H_{nl}^1, D_{-} / \sqrt{2} \doteq H_R^{10}, D_{+1} / \sqrt{2} \doteq H_R^1, D_{+2} / \sqrt{2} \doteq H_{nl}^{10}$$

where

$$\frac{1}{2^{\frac{1}{2}} H_R^1} = (H_p^1 H_{nl}^1)^{1/3} \left\{ (H_p^1)^{2/3} + (H_{nl}^1)^{2/3} \right\}^{\frac{1}{2}}$$

$$\frac{1}{2^{\frac{1}{2}} H_R^{10}} = (H_p^{10} H_{nl}^{10})^{1/3} \left\{ (H_p^{10})^{2/3} + (H_{nl}^{10})^{2/3} \right\}^{\frac{1}{2}}$$

If the D values are determined from the results of the Table 6, the altitudes (H_p^1, H_{nl}^1) and (H_p^{10}, H_{nl}^{10}) of the vertical dipoles respectively at the lowermost and the uppermost positions can be obtained by using the above formulae. The D values estimated from the Table 6 are summarized in the following table.

Boundary distance	D	D 1	D 2	D-
range of estimated distance	6 - 7 km	less than 4 km	7 - 10 km	7 - 10 km
mean value	6.5 km	less than 4 km	8.5 km	8.5 km

The calculation of H values obtained by putting these D values into the above formulae gives the following table.

H_n^{\min}	H_p^{\min}	H_n^{\max}	H_p^{\max}
4.6 km	less than 1.7 km	6.0 km	6.3 km

The minimum altitude of the dipole obtained here seems roughly to agree with the result $H_{nl} = 3.6$ km and $H_p = 1.4$ km, given by Malan and his colleagues (4,6) in South Africa. On the other hand the maximum altitude of the dipole given by the table is $H_p^{\max} > H_{nl}^{\max} \doteq 6$ km. However, if we consider the low

accuracy of the estimation of the distance of a lightning discharge, it will be meaningless to give the small difference

$$H_p^{\max} - H_{nl}^{\max} = 0.3 \text{ km}$$

some importances.

Therefore it will reasonable to consider that the separation of the two opposite electrical charges of a dipole decrease with

the increase in its altitude, and that the mean altitudes $(H_{nl}^i, H_p^i) / 2$ of all Ig dipoles take the values lying between the two extremum mean altitudes

$$(1.0^* + 4.6) / 2 \doteq 2.8 \text{ km and}$$

$$(6.0 + 6.3) / 2 \doteq 6.2 \text{ km}$$

The distances of lightning discharges indicated in the Table 6 were estimated from the knowledge concerning the polarity variation of the leader field changes with the stroke order of a multiple ground discharge together with the knowledges about the relation between the altitude of a ground stroke and the order of it given by Malan and his colleagues⁽⁶⁾.

As we shall see it in the following paragraph (B), our thunderstorm observations give the result that the altitude of a succeeding ground stroke in our country does not increase appreciably with the increase in the order of the stroke, hence the altitude of a later stroke of a multiple ground discharge in our country usually does not take so large a value as it does in south Africa, because the vertical extent of a thundercloud in our country is generally smaller than that in the tropical zone like South Africa. This result seems to agree fairly well with that obtained by Workman and his colleagues⁽¹⁰⁾ from the thunderstorm observation at Albuquerque in the United States. Considering these points we may conclude that the altitudes of ground strokes given by Malan⁽⁴⁾ are applicable only to the earlier strokes of a multiple ground discharge in our country. The adoption of Malan's values to the later strokes of a multiple ground discharge in our country will result in the overestimation of the stroke altitudes. This means that the maximum value of the vertical dipole altitude 6.2 km obtained in the above table is too large. Therefore some corrections are needed for the estimation of D values from the data of the Table 6. Taking these points into account we have estimated once more the D values on the basis of the data obtained at Maebasi, which has given the result in the following table.

Boundary distance	D +	D #1	D #2	D -
Mean value	6.5 km	less than 4.0 km	5.7 km	5.7 km

* We shall assume that the value H_{min}^i is roughly equal to the altitude of a thundercloud base about 1.0 km, which has been obtained from the thundercloud observation carried out in the district surrounding Maebasi-City.

From this we can obtain as before the various H values. The result is represented in Table 13.

Table. 13

Altitude	H_n^{\min}	H_p^{\min}	H_n^{\max}	H_p^{\max}
Estimated altitude	3.6 km	less than 1.7 km	4.0 km	4.1 km

Following this table, the minimum mean altitude and the maximum mean altitude of the Ig dipole will be given by $(3.6 + 1.0) / 2 \doteq 2.3$ km and $(4.0 + 4.1) / 2 \doteq 4.0$ km respectively, and the mean of these two extremums will take the value 3.2 km, which is a little lower than the altitude 3.4 km of a first ground stroke obtained from the duration of the first leader. As the Vertical distribution of the Ig dipoles has been assumed to be uniform, we must consider the mean of the two extremum altitude values in order to replace the dipole group with the dipole of a mean altitude. If we adopt the value 1.0 km of the altitude of the thundercloud base in the district round Maebasi in stead of < 1.7 km indicated in the Table 13, the altitudes of the averaged dipole \bar{H}_{n1} and \bar{H}_p will be given by

$$\bar{H}_{n1} = (4.0 + 3.6) / 2 \doteq 3.8 \text{ km.}$$

$$\bar{H}_p = (4.1 + 1.0) / 2 \doteq 2.5 \text{ km.}$$

Therefore an igniting discharge will be represented by a negative dipole, which is composed of the negative charge at an altitude $\bar{H}_{n1} = 3.8$ km and the positive charge at an altitude $\bar{H}_p = 2.5$ km., so that the separation of the dipole electricity will be 1.3 km.

Another method to estimate the altitudes of the two opposite charges of a vertical dipole is to measure the duration of the leader of a first ground stroke. As we have investigated in Section 2, the electromagnetic field changes due to the leader of a first ground stroke can roughly be divided into two categories, which correspond respectively to α type (3) and β type (11) stepped leaders confirmed with the photographic method. Table 14 represent the statistical results of measurement of stepped leader durations of these two types on the records of the field changes.

Our measurement of the two dimensional length L of a ground stroke channel along a trunk and the altitude H of it on the

photographic record gives the ratio about 0.9*

Types Sections Duration	α type leader	β type leader(*)		
	T_{α}	Tlg	TL	TlgL
Leader duration (median value)	9.0 ms	6.0 ms	14.0 ms	27.0 ms
Number of waveform records(**)	33	21	51	190

(*) Intermediate leaders between α type and β type (see Table 9 Section 3 (c)) are included in this statistics.

(**) The waveforms were selected so as to limit the distances of the discharges roughly less than 60 km.

The following table represents the statistical result of these measurements. Strictrly speaking, of course, this value can not be applited to the portion of a ground stroke channel other than

	Median value	Mean value	Number of data
$(H/L)_{II}$ *	0.896	0.891	42

* Two dimensional value

that appearing between the cloud base and the earth. Table 15 represents the progressive velocities of to the leader to the first stroke and to the air discharge, measured on out photographic records of lightning flashes.

The two velocities V_1 and V_2 included in the column $\alpha\beta$ type and β type represent the velocity before the variation of the stepped leader structure and that after the variation respectively; the

* $(H/L)_{II}$ value converted into three dimension will be
 $(H/L)_{III} = 0.83$

Table 15

Stepped leader Leader velocity	First leader velocity (Ground stroke)				Air discharge	
	α type	$\alpha\beta$ type and β type		Trunk of ground flash*		Branch of ground flash*
	V_α	V_1	V_2			
Mean value	4.2×10^7	4.2×10^7	1.8×10^7	4.4×10^7	3.2×10^7	1.2×10^7 cm/sec
Median value	6.6×10^7	4.2×10^7	1.6×10^7	3.1×10^7	3.2×10^7	1.4×10^7 cm/sec
Number of data	4	5		13	14	10

Stepped leader Leader velocity	Air discharge
Mean value	1.2×10^7 cm/sec
Median value	1.4×10^7 cm/sec
Number of data	10

velocity of the trunk of a ground flash represent the mean value along the whole length of a trunk and the statistics include all types of stepped leaders. The same is applied also to the case of the branch of a ground flash. The air discharges in the last column are all β type leaders. The altitudes of the two opposite charges of a Ig dipole can be estimated by adopting the values indicated in these three

tables as follows:

$$\text{Altitude of positive charge } \bar{H}_p = V_2 \times T_L \times (H/L)_{III} = 2.1 \text{ km.}$$

$$\text{Altitude of negative charge } \bar{H}_{n1} = V_\alpha \times T_\alpha \times (H/L)_{III} = 3.2 \text{ km.}^*$$

The separation of the dipole charges will be given by

$$\bar{H}_{n1} - \bar{H}_p = v_1 \times T_{Ig} \times (H/L)_{Ig} = 2.52 \times (H/L)_{Ig} \times 10^5 \text{ cm}$$

Following the above two methods of estimations, the mean separation of the dipole will be $\bar{H}_{n1} = \bar{H}_p = 1.1 \text{ } 1.3 \text{ km.}$ If

* As the progression an type stepped leader does not much influenced by the positive charge concentration at p, (see Fig. 16, II 4 (A)) and proceeds roughly at an uniform speed from n_1 to the earth, the $(H/L)_{III}$ value 0.83 obtained from the photographic measurement may be assumed to be applicable for the whole length of an α type stepped leader.

we assume that $\overline{H_{nl}} - \overline{H_p} = \overline{H_{nl}} - \overline{H_p}$ and take the average of the above two values, we shall get the relation $2.52 \times (H/L)_{Ig} = 1.2$, from which $(H/L)_{Ig} = 0.48$ results*. This may be attributed to the inclination as much as 60 degrees of the Ig dipole from the vertical axis. However, this results in the horizontal shift of the two opposite charge centers of an Ig dipole statistically as much as 2.0 km relative to each other.

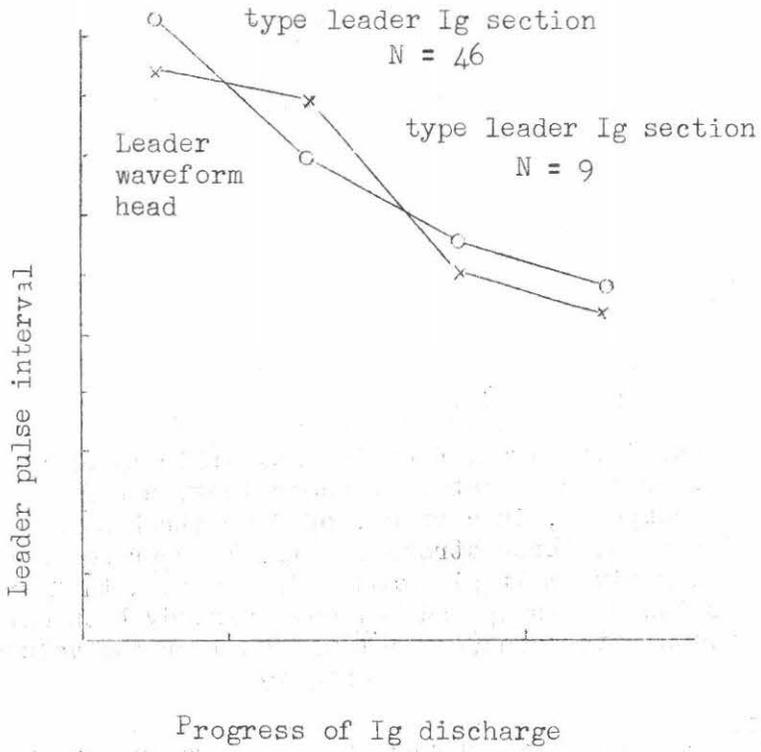
The conclusion of this inclined Ig dipole seems somewhat not to be plausible, because the electrical charge generations relating to a thundercloud should always be considered being active along a violent vertical upward stream of the air. Therefore the charges thus generated seems generally to be arranged on a vertical line, especially when we must consider the charge distributions in the lower portion of thundercloud. As the smallness of the $(H/L)_{Ig}$ value really comes from the T_{Ig} value taking rather a large value, so that to interpret these large T_{Ig} we are forced to infer the existence of a complex Ig discharge being composed of at least more than two stepped leader processes overlapping each other with an appropriate time separation. However, the regularity existing in the variation of leader pulse intervals with the progress of an Ig discharge represented in Fig. 17 seems to support the view of a inclined Ig dipole. Therefore these two explanations seem to complement each other and both may not be neglected. Table 16 gives the result of the estimation of H values using these two methods.

Table 16

Altitude	$\overline{H_p}$	$\overline{H_{nl}}$	$\overline{H_{nl}} - \overline{H_p}$
Mean value obtained with the two methods of estimations	2.1 - 2.5 km	3.2 - 3.8 km	1.1 - 1.3 km
Over all mean	2.3 km	3.5 km	1.2 km

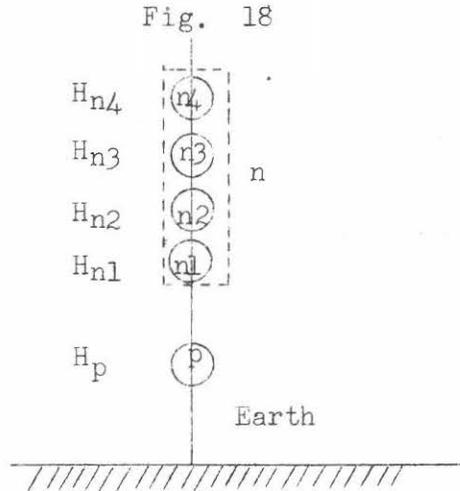
* The H/L value given by Schonland(12) $1/1.3 = 0.77$ seems to represent the mean value obtained from the measurement of ground flashes in the portion below the cloud base, so it will be reasonable that the value $(H/L)_{Ig}$ of the Ig discharge in a thundercloud is appreciably different from the (H/L) value given by Schonland.

Fig. 17



(B) Altitudes of successive ground strokes

Malan and Schonland⁽¹³⁾ showed that the successive strokes of a multiple ground discharge perform a function to neutralize the negative charge distributed in a vertical column inside a thundercloud successively from the lower most portion of it toward the upper portion of it. Let the negative charge distribution n_1, n_2, n_3, \dots contributing to each of the ground strokes be replaced by the respective spherical charge distributions, lying on a vertical line as illustrated in Fig. 18.



Our statistical investigation of the multiplicity of a ground discharge represented in Table 17 shows that, a negative discharge is composed, in average, of four strokes while a positive discharge, three strokes. Fig. 18 represents the case of the negative multiple ground discharge with four strokes. As the values H_p and H_{n1} have already been estimated in the previous paragraph (A), let us consider the values

Table 17

polarity	Positive ground discharge	Negative ground discharge	
	Method of - recording	Cont. waveform and Electrostatic field-meter	Cont. waveform
Stroke multiplicity (Mean value)	2.8	4.2	4.2
Number of data	6	77	69

H_{n2}, H_{n3}, \dots in this paragraph. There are several methods⁽⁶⁾ possible to estimate these H_n values, however, we shall consider the leader durations of successive strokes to obtain them.

As indicated in Fig. 19(a) the electromagnetic field change L produced by a dart leader of a successive, ground stroke will take the form of a negative ES pulse which precedes the R pulse indicated in figure, when the change is recorded with our short range waveform recorder at distance less than 5 km from the ground stroke. But, if the distance is increased beyond 7 - 8 km, the L field change comes out to have a form of a positive ES pulse, on which small high frequency radiation pulses of the same structure as those appearing on the waveform of the first leader of a ground discharge are superposed as illustrated in Fig. 19(b). The interpretation that this ES pulse in the L section of the waveform really originates from the dart leader preceding a successive ground stroke is supported by the out-break of a light pulse on the record of lightning luminosity changes coinciding with the L field change as illustrated in lower half part of the Fig. 19. Moreover, to see whether the ES pulses, like those marked with R in the Fig. 19, appearing on the waveform of a ground discharge really originate from the return strokes composing a multiple ground discharge, the time intervals between the R type ES pulses were measured on the CW records of ground discharges, and the probability distribution of them have been calculated, the result of which is illustrated in the Fig. 20 along with the probability distribution of stroke intervals obtained from the measurement of photographic record of lightning flashes for the sake of comparison. The general agreement between the two distributions in the Fig. 20 together with the above result concerning the L field change, clearly indicates the fact that the field change composing L and R ES pulse pairs really come from the leader return stroke combination of a multiple ground discharge. To know the variation of the dart leader duration with the order of a stroke involved in a multiple ground discharge, we limited the distances of ground discharges recorded with the short range waveform recorder not to exceed roughly 40 km, and measured the duration T_D of the L field change of each LR type pulse that correspond to one of the successive ground strokes on the CW records. Statistical result showing the variation of T_D values with the order of a stroke composing a multiple ground discharge is represented in the Table 18. We can obtain the altitude of each stroke from the respective T_D values in the Table 18, if we know the statistical velocity value of a dart leader. Concerning this point, the mean of the dart leader velocities measured on four photographic records of the leaders gives the value $\bar{v}_D = 4.0 \times 10^8$ cm/sec, however, it is questionable whether the value has a statistical meaning or not. Therefore

Table 18

Leader Statistical value Stroke order	Leader duration on T_D of a successive ground stroke*		
	mean value	Median value	Number of data
II	0.88 ms	0.8 ms	48
III	0.89	0.9	52
IV	0.86	0.85	42
V	0.93	0.9	36
VI	1.15	1.0	26
VII	1.20	1.05	20
VIII	1.03	0.9	15
IX	1.03	0.95	14
X	0.91	1.0	7
XI	1.40	1.4	5
XII	1.50	1.9	3
XIII	1.05	1.05	2
XIV	1.05	1.05	2
XV	0.8	0.8	1

* The distance of discharges being roughly less than 40 km

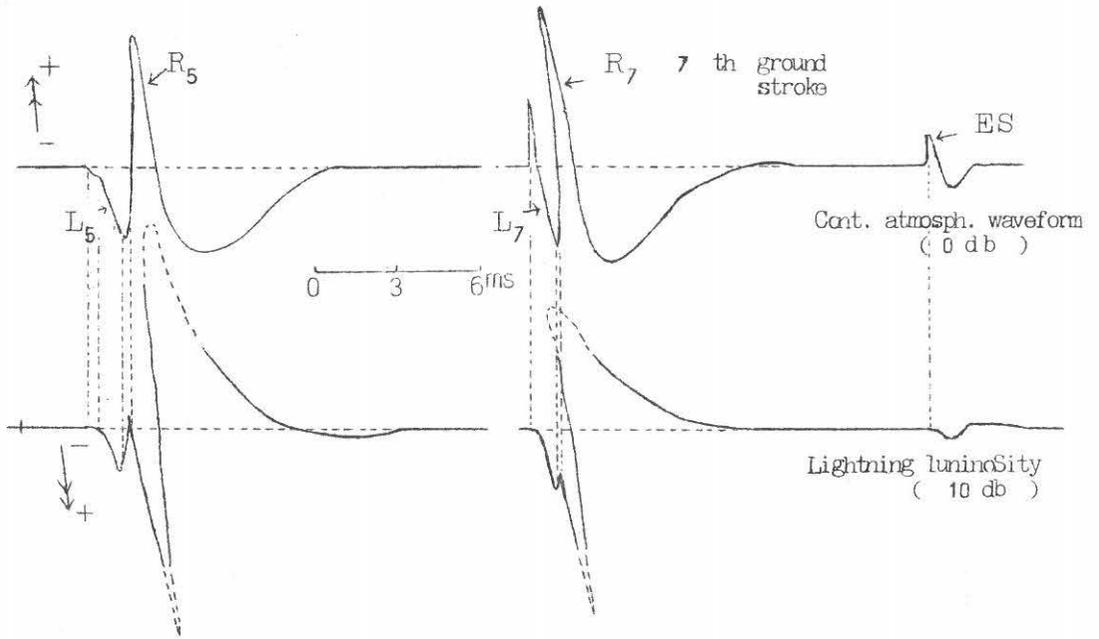
it would be better to consider the dart leader velocity $\bar{v}_D = 5.5 \times 10^8$ cm/sec given by Schonland and his colleagues(3) instead. Then the altitude of each successive ground stroke will be obtained from the relation $\bar{H}_i = 0.83 \times \bar{v}_D \times \bar{T}_{D_i}$, where \bar{T}_{D_i} is the mean dart leader duration relating to the i -th ground stroke given in the second column of Table. 18, and the factor 0.83 is introduced so as to correct the inclination of the discharging channel from the vertical axis. The Table 19 gives the result of this calculation, and the Fig. 21 is inserted to compare the results obtained in our country with those of Malan and Schonland(6) obtained in South Africa. The portion of the two curves with somewhat less reliability is represented with broken lines.

Table 19

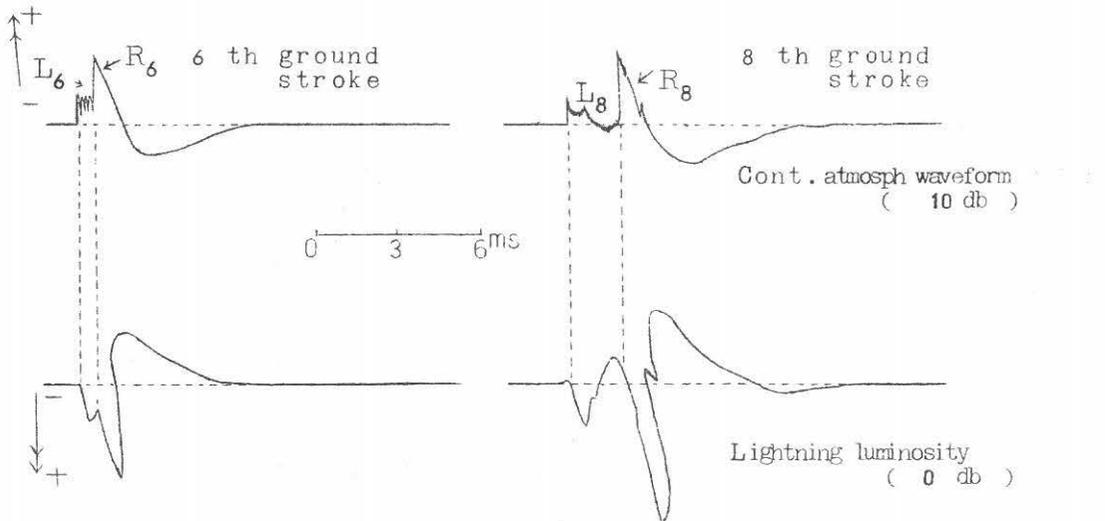
Stroke order	I	II	III	IV	V	VI	VII	VIII	IX	X	XV	XII	XV
Altitude of ground stroke	3.5 ^{km}	4.1	4.1	4.0	4.3	5.3	5.5	4.7	4.7	5.2*	4.5*		
Number of data	74	48	52	42	36	26	20	15	14	20	273		

* Mean value

Fig. 19

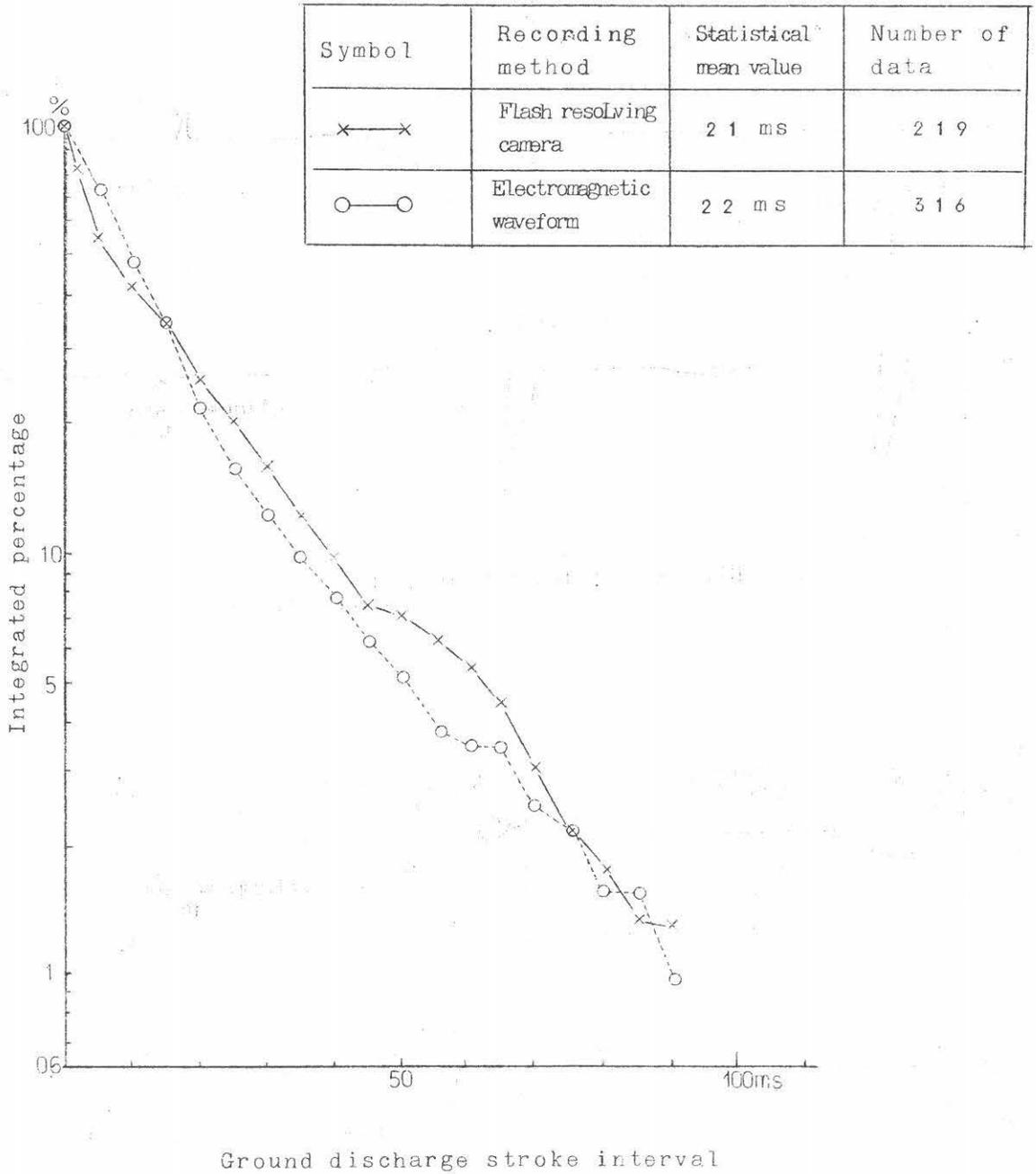


(a) Distance : Less than 5 km
(1959. 8. 18)

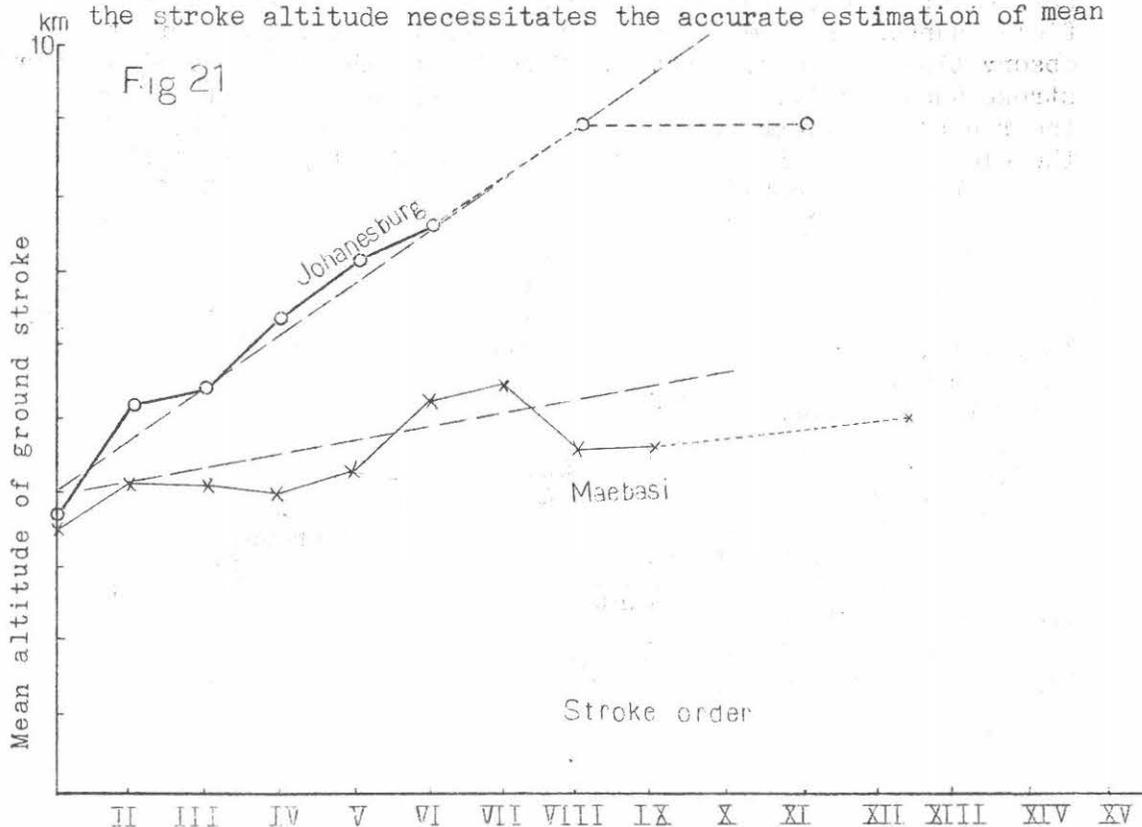


(b) Distance. 7-8 km (1959. 8. 18)

Fig. 20



The increase in the altitude with the stroke order is discernible on both of these two curves in the figure, but it is clear that the increase of the Maebasi curve is by no means so distinct as that of the Johannesburg curve. This may partly come from the fact that the dart leader method for obtaining the stroke altitude necessitates the accurate estimation of mean



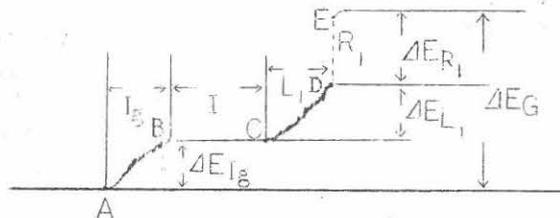
dart leader velocity and the each estimated value of the stroke altitude may severely be influenced by the fluctuation in leader velocities from case to case. However, a greater portion of the reasons why the two curves of the Fig. 21 not coinciding with each other seems, despite the above facts, to be attributed to the point that the vertical extent of a thundercloud growing upwards in the temperate zone like our country, is generally smaller than that of the cloud appearing in the tropical zone like Johannesburg. This may result in the reduction of the rate of increase in the stroke altitude with the increasing order of strokes. This tendency has already been pointed out in the previous paragraph A of this section concerning the observational result obtained by workman⁽¹⁰⁾ at Albuquerque in the United States.

5. Electrical charge contributing to a ground stroke

(A) Electrical charge discharged by the first ground stroke

To estimate the electrical charge relating to each of the ground stroke composing a ground discharge, it is necessary to obtain, at least, two simultaneous records of electrostatic field changes produced by a ground discharge at two different observation stations. However, if we assume the altitude of a ground stroke adequately, we can estimate the electrical charge from the record of electrostatic field changes at one station. If the electrostatic field change due to the first ground stroke is recorded with our waveform recorder at distances 6 - 20 km apart from the discharge, the field change will take the form illustrated in Fig. 2 (a) of the Section 2 Chapter II. The time sweep of these trigger waveforms has value 20 ms and is five times larger than the time constant 4 ms of the waveform recorder. Therefore, if a large stepwise electrostatic field change is recorded with this recorder, the deflection of the recorded waveform at the moment 2 ms after the appearance of the step field change will be reduced to less than 2/3 of the correct deflection, and the waveform recorded will not represent a step form, but will be deformed from it seriously. Now let us assume that the waveform corresponding to a ground stroke is recorded with a waveform recorder composed of an amplifier system with long enough time constant compared with the duration of the ground stroke field change. In this case the field change will be recorded without any deformation and will have the waveform illustrated in Fig. 22. Appleton and Chapman (14) pointed

Fig. 22



out that the field change produced by a ground stroke are generally composed of three portions, i.e., "a, b, and c." The "c" portion, however, is not represented in the Fig. 22, because the field change concerned with this section are nothing other than the portions "a and b". Let us consider a negative dipole contributing to Ig discharge of a first ground stroke (see Fig. 16, Section 4 A, Chapter II), and assume the altitudes of the positive and the negative charges of an Ig dipole being H_p and H_{n1} respectively, and the electrical quantities of them being Q_p and $-Q_{n1}$, respectively. If the distance of the ground discharge from the station is known, the field intensities E_A , E_B , E_C , E_D , and E_E at the moments corresponding respectively to the points A, B, C, D and E on the waveform of Fig. 22 will be expressed as follows:

$$\begin{aligned}
 E_A &= \frac{-2Q_{n1} H_1}{(H_{n1}^2 + D^2)^{\frac{3}{2}}} + \frac{2Q_p H_p}{(H_p^2 + D^2)^{\frac{3}{2}}} = -\frac{2Q_{n1}}{D^2} f(X_{n1}) + \frac{2Q_p}{D^2} f(X_p) \\
 E_B &= \frac{2\{Q_{n1} - Q_p - (1 - \epsilon_p) Q_{L1}\} H_{n1}}{(H_{n1}^2 + D^2)^{\frac{3}{2}}} - \frac{2Q_{L1}}{H_{n1}} \left[\frac{1}{(H_p^2 + D^2)^{\frac{1}{2}}} - \frac{1}{(H_{n1}^2 + D^2)^{\frac{1}{2}}} \right] \\
 &= -\frac{2\{Q_{n1} - Q_p - (1 - \epsilon_p) Q_{L1}\}}{D^2} f(X_n) - \frac{2Q_{L1}}{D^2} \frac{1}{X_{n1}} g(X_p, X_{n1}) \\
 E_C &\doteq E_B \\
 E_D &= -\frac{2Q_R H_{n1}}{(H_{n1}^2 + D^2)^{\frac{3}{2}}} - \frac{2Q_{L1}}{H_{n1}} \left[\frac{1}{D} - \frac{1}{(H_{n1}^2 + D^2)^{\frac{1}{2}}} \right] \\
 &= -\frac{2Q_R}{D^2} f(X_{n1}) - \frac{2Q_{L1}}{D^2} \frac{1}{X_{n1}} g(0, X_{n1}) \\
 E_E &= 0
 \end{aligned} \tag{1}$$

where $X_{n1} = H_{n1} / D$, $X_p = H_p / D$, $\epsilon_p = X_p / X_{n1}$

$$\begin{aligned}
 f(X) &= \frac{X}{(1+X^2)^{\frac{3}{2}}}, \quad g(X, Y) = \frac{1}{(1+X^2)^{\frac{1}{2}}} - \frac{1}{(1+Y^2)^{\frac{1}{2}}} \\
 Q_{n1} &= Q_p + Q_{L1} + Q_{R1}
 \end{aligned} \tag{2}$$

Q_{L1} is the electric charge distributed along the discharge channel by the leader process, Q_{R1} is the electric charge remaining inside the thundercloud and neutralized by the process of the following first return stroke. If the distance of the discharge becomes large, $x_{n1} \ll 1$, $x \ll 1$ will be satisfied.

In this case the formulae (2) will be approximated as

$$f(x) \doteq x(1 - 3x^2/2) \doteq x \quad g(x, y) = \frac{1}{2}(y^2 - x^2) \quad (3)$$

The rapid electrostatic field changes ΔE_{IG} , ΔE_{L1} and ΔE_{R1} (see Fig 22) produced respectively by the igniting discharge, the stepped leader, and the return stroke will be obtained by using the formulae (1) as

$$\left. \begin{aligned} \Delta E_{IG} = E_B - E_A &= \frac{2\{Q_p + (1 - \epsilon_p)Q_{L1}\}}{D^2} f(X_{n1}) - \frac{2Q_p}{D^2} f(X_p) \\ &\quad - \frac{2Q_{L1}}{D^2} \frac{1}{X_{n1}} g(X_p, X_{n1}) \\ \Delta E_{L1} = E_D - E_C &= \frac{2\epsilon_p Q_{L1}}{D^2} f(X_{n1}) - \frac{2Q_{L1}}{D^2} \frac{1}{X_n} g(0, X_p) \\ \Delta E_{R1} = E_E - E_D &= \frac{2Q_{R1}}{D^2} f(X_{n1}) + \frac{2Q_{L1}}{D^2} \frac{1}{X_{n1}} g(0, X_{n1}) \end{aligned} \right\} (4)$$

If $D \gg H$, so that the condition $x_p \ll 1$, $x_{n1} \ll 1$ being satisfied, the formulae (4) will be approximated as

$$\left. \begin{aligned} \Delta E_{IG} &= \frac{2\{Q_p + (1 - \epsilon_p)Q_{L1}\}}{D^2} X_{n1} - \frac{2Q_p}{D^2} X_p - \frac{Q_{L1}}{D^2} \frac{X_{n1}^2 - X_p^2}{X_{n1}} \\ \Delta E_{L1} &= \frac{\epsilon_p Q_{L1}}{D^2} (2X_{n1} - X_p) \\ \Delta E_{R1} &= \frac{2Q_{R1} + Q_{L1}}{D^2} X_{n1} \end{aligned} \right\} (5)$$

Let us introduce two constants α , β_1 , defined by

$$\Delta E_{Ig} / \Delta E_{R1} = \alpha \quad \Delta E_{L1} / \Delta E_{R1} = \beta_1$$

Put this relation into the formulae (5), the following equation will be obtained.

$$\left. \begin{aligned} Q_{L1} &= \frac{2\beta_1}{\epsilon_p(2-\epsilon_p) - \beta_1} Q_{R1} \\ Q_p &= \frac{\alpha\epsilon_p(2-\epsilon_p) - \beta_1(1-\epsilon_p)^2}{(1-\epsilon_p)\{\epsilon_p(2-\epsilon_p) - \beta_1\}} Q_{R1} \\ Q_{n1} &= 1 + \frac{2\beta_1}{\epsilon_p(2-\epsilon_p) - \beta_1} + \frac{\alpha\epsilon_p(2-\epsilon_p) - \beta_1(1-\epsilon_p)^2}{(1-\epsilon_p)\{\epsilon_p(2-\epsilon_p) - \beta_1\}} Q_{R1} \end{aligned} \right\} (6)$$

As we have already investigated, the electromagnetic waveform due to the first ground stroke recorded with our recorder is subjected to a considerable deformation and does not reproduce the field change correctly, because of the short time constant (4 ms in the present case). The field change ΔE_{R1} due to a return stroke, however, can be recorded quantitatively without any serious error, since the field change ΔE_{R1} is generally a very rapid phenomenon and completed within the time length of the order of 0.1 ms which is small enough compared with the time constant of the recorder. Moreover the field changes produced by the Ig section or by the L section involved in a preliminary discharge also sometimes are completed within a time length shorter than the time constant of the recorder. In these cases we can also estimate the magnitude of the field change ΔE_{Ig} ; and ΔE_{L1} with a measuring error roughly less than 30%. Table 20 represent the statistical estimation of α and β_1 values obtained from the data satisfying the above limitation caused by the recorder time-constant. In these measurements, the discharges which were recorded at distances ranging 15 - 40 km were measured to satisfy the condition $x = H/D \ll 1$.

If we adopt the mean values of H_p and H_{n1} represented in the

Table 20

	Mean value	Median value	Number of data
	0.289	0.296	16
	0.300	0.292	9

Table 16 Section (A) Chapter II, the value ξ_p will be given by $\xi_p = H_p/H_{n1} = 0.68$. This value together with the mean values of α β_1 in Table 20 being put into the formulae (6) gives the following relations.

$$\begin{aligned} Q_p &= 0.360 Q_{n1} \\ Q_{L1} &= 0.323 Q_{n1} \\ Q_{R1} &= 0.317 Q_{n1} \end{aligned} \quad (7)$$

Q_{R1} can be obtained through the elimination of Q_{L1} from the third one of the formulae (4) using the first relation of the formulae (6) as follows.

$$Q_{R1} = \frac{\frac{1}{2} D^2}{f(X_{n1}) + \frac{2\beta_1}{\varepsilon_p(2-\varepsilon_p)-\varepsilon_1} \frac{1}{X_{n1}} g(0, X_{n1})} \Delta E_{R1} \quad (8)$$

Putting $\beta_1 = 0.3$, $\varepsilon_p = 0.68$ into this relation we get

$$Q_{R1} = \frac{D^2}{1.8 \left\{ f(X_{n1}) + 1.02 \frac{1}{X_{n1}} g(0, X_{n1}) \right\}} \Delta E_{R1} \times 10^{-4} \quad (8')$$

where D , ΔE_{R1} , Q_{R1} are expressed in km, V/m, coul. respectively. The magnitude ΔE_{R1} was measured on each electromagnetic waveform due to a ground stroke having appeared within the range of distances 5 - 30 km, where the estimation of the distance was made with visual, or acoustical method. Putting the estimated pair values of ΔE_{R1} and D into the equation (8') we can get Q_{R1} for each ground stroke, the statistical result of which is summarized in the following table.

	Mean value	Median value	Number of data
Q_{R1}	2.48 coul.	2.53 coul.	8

The values Q_{n1} , Q_p and Q_{L1} can be obtained from the value of Q_{R1} by using the formulae (7). Table 21 represents the result of this calculation. These results combined with those represented in Table 16 lead us to the conclusions that a negative dipole contributing to a igniting discharge I_g , must statistically be composed of a negative electrical charge of - 8 coul located at an altitude 3.5 km and a positive electrical charge of 2.9 coul located at an altitude 2.3 km above the ground.

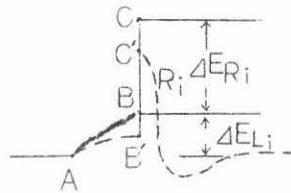
Table 21

Q_{n1}	Q_p	Q_{L1}	Q_{R1}
8.0 coul.	2.9 coul.	2.6 coul.	2.5 coul.

(B) Electricity discharged by a succeeding ground stroke

The electrical charge contributing each of the successive ground strokes can also be estimated with the same method as described in the previous paragraph A. The electromagnetic field change due to one of the successive ground strokes recorded outside the field reversal distance, but not very distant from it, will have the waveform illustrated in Fig. 23, which assumes a typical ground stroke producing the stepwise field change without a "c" portion.

Fig. 23.



Let the altitude and the electrical charge of a succeeding ground stroke be H_{ni} and Q_{ni} respectively, and denote the discharge distance with D' , the electrostatic field intensities E_A , E_B and E_C at the moment corresponding respectively to the points A, B and C in Fig. 23 will be represented by the following relation similar to the formulae (1) in the previous paragraph A.

$$\left. \begin{aligned}
 E_A &= - \frac{2 Q_{ni}}{D^2} f(X_{ni}) \\
 E_B &= - \frac{2 Q_{Ri}}{D^2} f(X_{ni}) - \frac{2 Q_{Li}}{D^2} \frac{1}{X_{ni}} g(0, X_{ni}) \\
 E_C &= 0
 \end{aligned} \right\} (1)$$

where $x_{ni} = H_{ni}/D$ $Q_{ni} = Q_{Li} + Q_{Ri}$ ($i=2,3,4, \dots$)

Using these formulae, the electrostatic field changes ΔE_{Li} and ΔE_{Ri} in Fig.23, which respectively correspond to a dart leader and the following return stroke, will be represented as

$$\left. \begin{aligned} \Delta E_{Li} = E_B - E_A &= \frac{2Q_{Li}}{D^2} \left\{ f(X_{ni}) - \frac{1}{X_{ni}} g(0, X_{ni}) \right\} \\ \Delta E_{Ri} = E_C - E_B &= \frac{2Q_{Ri}}{D^2} f(X_{ni}) + \frac{2Q_{Li}}{D^2} \frac{1}{X_{ni}} g(0, X_{ni}) \end{aligned} \right\} (2)$$

If $D \gg H_{ni}$ so that the condition $x_{ni} \ll 1$ is satisfied, the approximation (3) in Paragraph A can be applied to this case, and the formulae (2) will be simplified as follows:

$$\left. \begin{aligned} \Delta E_{Li} &= \frac{Q_{Li}}{D^2} X_{ni} \\ \Delta E_{Ri} &= \frac{2Q_{Ri} + Q_{Li}}{D^2} X_{ni} \end{aligned} \right\} (3)$$

Let us introduce β_i, γ_i defined by $\Delta E_{Li} / \Delta E_{Ri} = \beta_i$,
 $\Delta E_{Ri} / \Delta E_{R} = \gamma_i$

and eliminate ΔE 's from these equations by using the formulae (5) in Paragraph A, together with the above formulae (3), the result of which will be

$$\left. \begin{aligned} \frac{\Delta E_{Li}}{\Delta E_{Ri}} &= \frac{Q_{Li}}{2 Q_{Ri} + Q_{Li}} = \beta_i \\ \frac{\Delta E_{Ri}}{\Delta E_{Ri}} &= \frac{2 Q_{Ri} + Q_{Li}}{2 Q_{Ri} + Q_{Li}} \quad \varepsilon_{ni} = \gamma_i \end{aligned} \right\} (4)$$

where $x_{ni}/x_{n1} = E_{ni}$.

Combining the formulae (4) with the formulae (6) in Paragraph A, Q_{ni}, Q_{Li}, Q_{Ri} will be represented in terms of Q_{n1} as follows.

$$\left. \begin{aligned} Q_{Li} &= \frac{2 \beta_i}{1 + \beta_i} Q_{ni} \\ Q_{Ri} &= \frac{1 - \beta_i}{1 + \beta_i} Q_{ni} \\ Q_{ni} &= \frac{\gamma_i (1 + \beta_i)}{\varepsilon_{ni}} \lambda \left(\frac{\beta_1}{\varepsilon_p (2 - \varepsilon_p) - \varepsilon_1} \right) Q_{n1} \end{aligned} \right\} (5)$$

$$\text{where } \frac{1}{\lambda} = 1 + \frac{2 \beta_1}{\varepsilon_p (2 - \varepsilon_p) - \beta_1} + \frac{\alpha \varepsilon_p (2 - \varepsilon_p) - \beta_1 (1 - \varepsilon_p)^2}{(1 - \varepsilon_p) \{ \varepsilon_p (2 - \varepsilon_p) - \beta_1 \}}$$

(See formulae (6), Section 5A)

As pointed out in Paragraph A, when the electromagnetic field change due to a successive ground stroke is recorded with the short range waveform recorder, the field change will be subjected to a considerable deformation which result from the short time constant (300 micro-sec., in this case) of the recorder. This point is illustrated with the broken line in Fig. 23. The field change ΔE_{Ri} produced by a return stroke, however, is usually very rapid and usually completed within a time of the order 10 micro-sec., so that the relation $E_C' - E_B' = E_C - E_B = \Delta E_{Ri}$ must be concluded.

In contrast to this, according to the results indicated in Table 18 of the Section 4B, the duration of a dart leader is generally of the order of 1 ms and about three time as large as the time constant of our waveform recorder. Therefore the record of a dart leader field change which continues through this time length must be subjected to an appreciable deformation as illustrated in the figure, and the ΔE_{Li} value measured on the waveform will not give a correct value. However the electrostatic field change due to a dart leader does not always progress uniformly, and some of the records of dart leader field changes actually indicate an abrupt variation as illustrated in the waveform of Fig. 19(b) in Section 4 B. In this case the field change due to a dart leader in the later period of it slows down appreciably in contrast to the very rapid speed at the beginning of it, and the greater part of the resultant field change ΔE_{Li} may be attributed to the rapid portion of it, that is, the contribution from the slow portion may be neglected without any serious error. Therefore on the waveforms of this type of dart leaders we may expect the possibilities to estimate ΔE_{Li} . To satisfy the condition $x_{ni} \ll 1$ we have picked out the waveforms of ground discharges whose distances from the observation station were likely distributed roughly 20 - 40 km, judged from the gain of the waveform recorder as well as from the electrostatic component of the waveforms. Further out of the waveforms thus picked out, we have selected such ones whose dart leader sections represented the structures just described and measured the values E_i and E_{Ri} on the rapid L_i and R_i sections of the selected waveforms respectively. Now the values β_i , r_i can be obtained by putting these ΔE_{Li} and ΔE_{Ri} values into the formulae (4), the result of which is represented in the Table 22.

Table 22 (a)

Stroke order	I	II	III	IV	V	VI-VIII	II-VIII
β_i (Mean value)	0.300	0.258	0.446	0.375	0.287	0.293	0.345
Number of date	9	7	7	6	6	5	31

Table 22 (b)

Stroke order	I	II	III	IV	V	VI	VII	L-VII
γ_i (Mean value)	1	0.497	0.896	0.737	0.737	0.431	0.588	0.897
Number of date	-	31	23	21	15	11	6	107

The coefficients of Q_{ni} 's in the first two relations of the formulae (5) can be calculated by adopting the β_i value indicated in Table 22 (a). The result is represented in the Table 23.

Table 23

stroke order	II	III	IV	V	VI - VIII
$2\beta_i/(1+\beta_i)$	0.411	0.617	0.545	0.448	0.454
$(1-\beta_i)/(1+\beta_i)$	0.591	0.383	0.454	0.562	0.548

As to the **third** relation of the formulae (5), the comparison of the coefficient of this relation with those of formulae (6), (7) in the previous paragraph A will give

$$1 + \frac{\beta_1}{\epsilon_p(2-\epsilon_p)-\beta_1} = 1.51 \quad \lambda = 0.316$$

It follows that $\lambda \left(1 + \frac{\beta_1}{\epsilon_p(2-\epsilon_p)-\beta_1}\right) = 0.478$. From this, the third relation

of the formulae (5) can be written as:

$$Q_{ni} = 0.478 \frac{\gamma_i(1+\beta_i)}{\beta_{ni}} Q_{n1} \quad (6)$$

$E_{ni} = H_{ni}/H_{n1}$ in the formulae (6) will be estimated by using the

H_{ni} value indicated in Table 19 of Section 4 B. Table 24 is the result of this estimation.

Table 24

Stroke order	I	II	III	IV	V	VI	VII	VIII	II-VIII
E_{ni}	1,00	1.22	1.22	1.19	1.28	1.58	1.64	1.42	1.33

Combining the respective values indicated in the Table 22 and 24, the coefficient of the formulae (6) can be obtained stroke by stroke. Table 25 represent the result.

Table 25

Stroke order	II	III	IV	V	VI	VII
$0.478 \frac{r_i(1+B_i)}{E_{ni}}$	0.446	0.507	0.405	0.354	0.168	0.222

If we assume $Q_{n1}=8.0$ coul following Table 21 in Paragraph A, and adopt the coefficient value of Table 25, each Q_{ni} will be calculated by using the formulae (6), which results in the Table 26 (a).

Table 26 (a)

Stroke order	I*	II	III	IV	V	VI	VII	II-VII	I-VII
Q_{ni}	8.0	3.7	4.0	3.2	2.8	1.3	1.8	2.8	3.5 coul.

* The value indicated in Table 21 in Section 5A.

Putting the respective values of the Table 26 (a) into the first two relations of the formulae (5), we can easily get the values Q_{Li} and Q_{Ri} . The result is represented in the Table 26 (b)

Table 26 (b)

Stroke order	I*	II	III	IV	V	VI	VII	I-VII	II-VII
QLi	2.6	1.5	2.5	1.7	1.2	0.6	0.8	1.55	1.4 coul.
QRi	2.5	2.2	1.5	1.5	1.6	0.7	1.0	1.59	1.4

* The value in Table 21 in the Section 5A.

Table 26 (a) indicates a decrease in Q_{ni} with the increase in the stroke order. This seems to mean that the electrical charge density of the negative column n (see Fig. 1, Section 1), in a thundercloud generally reduces with the increase in the altitude.

The right-most column of Table 26(a) indicates the mean electrical charge per ground stroke, which amounts to 3.5 coul. This is only 54 % of the Q_{ni} value, = 6.5 coul, reported by workman (10). But if we assume that the mean stroke number per ground discharge is four (see Table 17 Section 4 B, Chapter II), the electrical charge dissipated by a ground discharge will be 18.9 coul according to what the Table 26 (a) indicates.

Therefore as an average, about 20 coul of the negative electricity will be consumed by a ground discharge. Concerning of the total electrical charge contributing to a ground discharge it is sufficient to consider only the process composed of leader and return strokes, but it is necessary to take the electrical charge consumed by the junction streamer process in the intervals between ground strokes into account. Let the total electrical charge dissipated by a ground discharge be Q_G , and those dissipated by individual ground strokes, and those dissipated by junction streamer processes be $\sum Q_{ni}$ and Q_J respectively, then Q_G will be written as

$$(7)$$

Concerning the electrical charge dissipated by a lightning discharge, the data reported by workman and Holzer(15) were adopted for our statistical investigation. Table 27 shows the result of this investigation, in which Q_G and Q_C represent the total electrical charge contributing to a ground discharge and that contributing to a cloud discharge respectively. Putting the value $Q_G = 44$ coul into the formula (7), we can get Q_J indicated in Table 28

Table 27

Lightning discharges	Statistical value	Mean value	Number of data
	Ground discharge Q_G		44 coul.
Cloud discharge Q_C		32 coul.	16

Table 28

Q_G	Q_{ni}	Q_J
44 coul.	19 coul.	25 coul.
100 %	43.2 %	56.8 %

The table indicates that the electrical charge dissipated by the process of ground strokes Q_{ni} must be inferred to occupy somewhat a smaller portion of the total charge Q_G than the charge dissipated by the junction streamer process Q_J does occupy. It has been cleared out in Section 3A that the discharge process performed by a junction streamer is essentially a discharge taking place inside a thundercloud, and it consists of the upward movement of a positive charge. This result in lowering the negative electrical charge distributed inside of a negative column n (see Fig. 1 Section 1 chapter II).

Therefore the portion of a thundercloud contributing to a junction streamer process must be supplied with positive electrical charge from the earth's surface at certain stages of a ground discharge, through a certain continuous or discrete process. It is well known that the return strokes composing a ground discharge perform an important role of supplying positive electricity to the lower portion of a thundercloud, however, following the results of this paragraph, the positive electricity elevated with this process to the cloud occupies only less than 50 % of the total negative charge which must be neutralized by a ground discharge. Therefore it is evident that the process which connects the junction streamer discharge in the cloud with the earth's surface and performs a role to lower

the electrical charge Q_j , contributing to the junction process, from the cloud to the earth must be sought in the discharge mechanisms other than return ground strokes. The rapid field changes described in this section are concerned with the first two of the "a, b and c" portions⁽¹⁴⁾ of the field change due to a ground stroke. If we take these points into account, it will be reasonable to infer that the process which connects the junction streamer discharge with the earth is likely constructed from discharge mechanisms which produce the "c" portion of the field change appearing after the completion of the "b" portion corresponding to a return stroke. Malan (16) concluded on the basis of his photographic observation of lightning flashes the existence of a ground discharge, whose channel built up by the previous return stroke in the space between cloud and earth, continues its luminosity through the first half period of the time interval between strokes till to the appearance of the succeeding one. If we consider the statistical evidence that a ground discharge as a mean must be expected to be composed of four strokes, it will be evident that even in such cases, where the above luminosity continuation is not so clear as Malan's report, the electric current of the order of 500 amp, which flows through the lightning channel remaining after the completion of a preceding return stroke during the first half period of the stroke interval, will be sufficient to elevate the electrical charge in total of about 20 coul from the earth's surface toward the lower portion of the cloud. According to our estimations, a stepped leader preceding the first return stroke usually necessitates an electric current of about 270 amp*, hence it follows that the above 500 amp of the electric current flowing from the earth to the cloud is only 1.85 times as large as the mean electric current of a stepped leader. Therefore, even though the existence of such a continuing discharge channel may be expected, it will be very difficult to photograph it because of the very weak luminosity of the discharge. We have not succeeded, till to the present, to photograph any such a weakly luminous channel continuing for a time length of the order of 10 ms after the outbreak of a return stroke.

* Let the electrical charge concerned with a stepped leader be 2.6 coul. (see Table 26 (b)), and the length of the discharge channel be $3.5/0.83 = 4.2$ km (see Table 16 section 4 A, Chapter II), the linear density of electrical charge distributed along the discharge channel will be $2.6/4.2 \times 10^{-5} = 6.2 \times 10^{-6}$ coul/cm. As the mean value of the progressive velocity of the stepped leaders is 4.4×10^7 cm/sec. (see Table 15 Section 4 A, Chapter II), the mean electric current of a stepped leader will be $6.2 \times 10^{-6} \times 4.4 \times 10^7 = 270$ amp.

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