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Use of Lightning Flash Counters as a Scientific Tool to deduce some Characteristics of Lightning in Sri Lanka

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Abstract: Lightning Flash Counters are relatively inexpensive devices for registering lightning activity in the neighbourhood of a given location. They are usually used in lightning warning systems in places of work where lightning poses a hazard. In the present work, it is shown how they can be used as a scientific tool to extract useful information about lightning parameters.

The following characteristics of lightning occurring in the neighbourhood of Colombo, Sri Lanka, have been deduced.

(*a*) The number of cloud to ground flashes per square kilometer per year is about 0.65.

(*b*) The centre of charge brought down by the leader of a first return ground stroke is heavily concentrated towards the lower end of the leader and is at an altitude of about 0.65 km.

(*c*) The ratio of intra-cloud lightning flashes to cloud to ground lightning flashes is at least as high as 8.5.

(*d*) Current bursts in intra-cloud flashes appear to be stronger and sharper than usually imagined.

1. Introduction

Lightning Flash Counters (LFC's) are relatively inexpensive devices for registering lightning activity in the neighbourhood of a given location. They are designed to be triggered by the electric field change which results from a lightning discharge,[3] and are used as lightning warning systems in factories and other places of work where lightning poses a hazard. But few attempts have been made to use them as a scientific tool in research on lightning.

There are great variations and uncertainties in the properties of lightning discharges and it is not easy to assess what different types of LFC do count. To introduce some measure of uniformity, the Conference Internationale des Grands Reseaux Electriques (CIGRE) recommended that a standard type of LFC should be used everywhere and gave specifications for such a standard counter. Yet it was not too clear what in fact this standard counter would count, CIGRE recommended that the standard counter should have a maximum response at a frequency of 500Hz and that the response should drop off equally at frequencies 500n Hz and 500/n Hz where n is a positive real number. For $n = 5$ they specified that the response should be 10/17 of the maximum response at 500Hz. It was also required that the counter should be locked for a time interval of one second after a count so that the next registration is possible only after this time. This requirement was made to avoid multiple counts from a multi-stroke flash.[11]

CIGRE recommended a horizontal antenna system, but this was found to be inconvenient and many workers in different countries replaced the horizontal antenna with a simpler vertical antenna and modified the counter circuit so that the response of these counters was almost the same as that of the standard CIGRE counter.[1-10]

Two vertical antenna counters called the VO3 and the VO4 were developed at the Institute of High Voltage Research, University of Uppsala, by E. Pisler. The VO3 had electrical characteristics and counting threshold closely similar to the standard CIGRE counter, and both counters give almost identical counts to thunderstorms when operated together side by side. The VO4 was designed to operate with the same antenna as the VO3 and to have the same frequency response pattern as the VO3 but with a maximum response centred at 10 KHz instead of 500Hz. A sinusoidal voltage fed into the antenna triggers both counters at a threshold peak voltage amplitude of 15.1 volt at their respective maximum response frequencies.

Kannangara[9] observed an interesting counting pattern as a thunder storm approaches when a VO3 and a VO4 were operated together in Uppsala in May 1978. As the storm approaches from a distance, the VO4 starts counting first. This happens well before there is any visible or aural evidence of the approaching storm at the site of the counter. As the storm approaches closer, the VO3 begins to register in coincidence with the VO4. When the storm is close enough for thunder to be distinctly heard, there is a short period where the VO3 counting rate increases and registers many more counts than the VO4. When the storm is almost overhead, the VO4 counting rate picks up and catches up with the VO3 rate. The pattern repeats itself in reverse order as the storm recedes. A tentative explanation of this phenomenon was given by Kannangara *et al.*[9]

It was decided that an exhaustive test of the phenomenon should be made in Sri Lanka which lies a few degrees North of the geographic equator, where there is abundant lightning and where facilities for using visual observers of thunderstorms 24 hours a day were relatively favourable.

2. The present investigation

A VO3 and a VO4 were installed in the premises of the Department of Meteorology, Sri Lanka, in Colombo in August 1978. Three hourly counter readings are taken throughout the day and night as a matter of routine by the officers of the Meteorological department, at 0230 hrs, 0530 hrs, 0830 hrs, 1130 hrs, 1430 hrs, 1730 hrs, 2030 hrs and 2330 hrs LST. 0530 hrs LST corresponds to 12 midnight GMT. Continuous records of the simultaneous counter readings are available from the 21st August 1978.

Individual counts from the two counters were also recorded at various times on a pen chart recorder moving at a speed of 1 foot per hour. A count on the VO3 was registered as a spike about 10mm long and a count on the VO4 as a spike about 5mm long. A coincident count on both counters gave a spike about 18mm long. Pen chart records taken as a storm approached and receded from the counting site clearly showed the same counting pattern as was first observed by Kannangara in Uppsala in 1978. Examples of these pen chart records and one year's counting data from 11th September 1978 to 21st August 1979 analysed on a six hour basis using the six hourly reports of thunder from the 20 meteorological substations referred to earlier were reported by Kannangara,[6] and Kannangara and Abhayasinghe Bandara.[7] It was apparent from this exercise that the counting data should be analysed on a shorter time period basis and that aural reports of thunder must be received from more observing stations in the area round Colombo, especially at a distance between about 20km and 60km from Colombo.

At the beginning, six hourly reports of aural observations of thunder were received from 20 Meteorological substations located in different parts of Sri Lanka. From February 1979, 17 of these meteorological stations together with 10 Physics teachers in schools scattered around an area extending to about 70km from Colombo were organised to make hourly records of thunder activity in their areas day and night.

This paper reports an analysis of one year's counting data taken from the 1st March 1979 to the 29th February 1980 analysed on a three hour basis, using the additional observers of lightning from schools.

Figure 1 shows a map of Sri Lanka showing the locations of the 27 stations which kept hourly records of thunderstorm activity. These records were kept on specially prepared forms where 24 cages were provided for each day corresponding to the 24 hours of the day and the observer marked a T in the appropriate cage corresponding to the day and hour in which he heard thunder. Station 1 corresponds to Colombo where the counters were sited. Keeping in mind that these observers were not specially employed to keep a vigilant ear for thunder, but were expected to record a T if they were aware of thunder in the normal course of their daily activities, the authors estimate that they would reliably report T only if the thunder activity occurred within a distance of 10km from them.

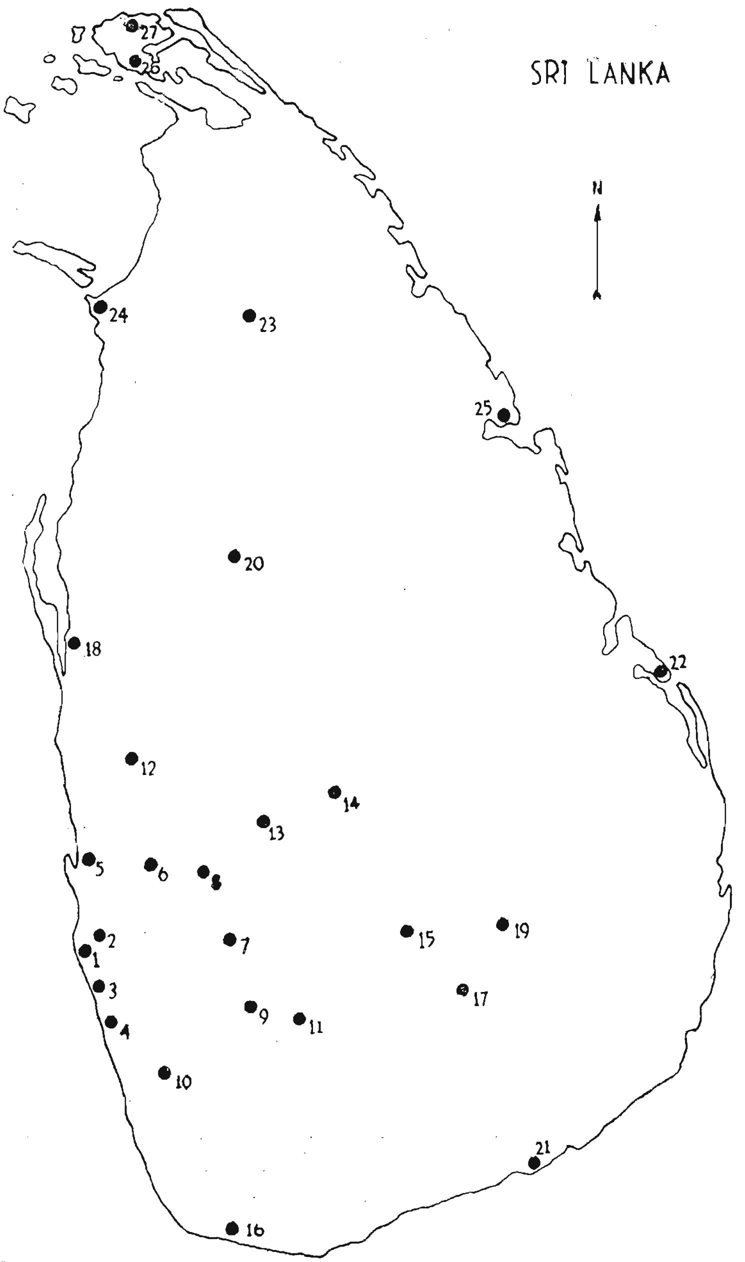


Figure 1. Stations sending in reports of thunder

The main experimental exercise in this investigation was to correlate the recordings of T sent in by the 27 observers with the three hourly counts read off the counters. There were 2928 three-hour periods in the year under consideration. Out of these, counter data and T reports were available for 2905 periods.

For each counting period of three hours the appropriate T reports were scanned and the closest station (CS) reporting T during that three hour period was determined. Table 1 gives a comprehensive analysis of the counting data in relation to the CS reporting T.

In this table, the first column gives the station number which corresponds to the numbers marked in figure 1. Station 1 is Colombo where the counters were installed. The second column gives the actual distance of each station from station 1. It is assumed that lightning activity within 10km of an observing station will result in thunder being heard so positively that a T will be marked by the observer in the appropriate cage of the form given to him. In the case of two stations close together like 1 and 2, in the vast majority of cases when 2 hears thunder, so will also 1, except when the activity is beyond 10km from 1 but within 10km of 2. Thus the effective distance of the lightning activity from 1 when 2 is CS is not its actual distance of 3km from 1 but about 11.6km. Similarly effective distances have been worked out for the other observing stations and these are given in column 3.

A scrutiny of columns 4 and 5 indicates that our estimates of effective distances of an observing station is sound. For example, stations 1, 2 and 3 which are close to each other, reported T during roughly the same number of three hour periods as should be expected. But station 2 was the CS on only 72 out of 320 occasions and station 3 on only 126 out of 361 occasions. These proportions roughly correspond to the areas round each station which are within 10km from it but greater than 10km from station 1.

In the case of CS being station 1, on the assumption that a thunderstorm approaching within a distance of 10km will result in a T being recorded, the closest approach of a thunderstorm could be anywhere within a distance of 10km from station 1. The average distance of closest approach would then be 6.67km.

In the first column, station O signifies none of the stations reported T. Column 5 indicates that there were 1677 such periods and columns 6 and 7 indicate that during these periods a total of 104 counts and 502 counts respectively were registered on the VO3 and VO4. These may be due to thunder activity over the sea, but it must be remembered that an unavoidable personal factor enters into the observations of T. One cannot expect a T to be entered on the record sheets with 100 percent efficiency when thunder is heard in the area of an observer's station. In the case of Meteorological observers they are expected to keep a 24 hour vigil but lapses do occur. In the case of the observers used from schools, however interested and devoted they may be, one has to expect cases of missed T especially during the sleeping hours. Also one has to expect the marking of a T in the wrong cage occasionally. Even with these obvious uncertainties the figures in table 1, especially a study of columns 8 and 9 and also columns 14 and 15, will indicate that the observers in this experiment have sent in reliable reports and that the table gives a fairly accurate picture of the actual state of affairs and that valid conclusions can be drawn from the numbers displayed therein.

TABLE 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Station Number	Distance Km	Effective Distance Km	Three-hour Periods T Reported	Periods Station CS	Total Counts VO3 when CS	Total Counts VO4 when CS	Counts per Period VO3 when CS	Counts per Period VO4 when CS	VO4/VO3 when CS	Zero Counts VO3 when CS	Zero Counts VO4 when CS	Zero Counts both when CS	Fraction Zero VO3 when CS	Fraction Zero VO4 when CS	Fraction Zero both when CS	CS and VO3 > VO4	CS, VO3 > VO4 and VO3 > 10	CS, VO3 or VO4 > 10	CS, VO3 or VO4 > 50	CS, VO3 or VO4 > 100	CS, VO3 or VO4 > 500	CS, VO3 or VO4 > 1000	CS, both VO3, VO4 > 50	CS, both VO3, VO4 > 100	CS, both VO3, VO4 > 500
1	0	6.67	360	360	21948	30789	60.97	85.53	1.4	44	8	2	0.12	0.02	0.005	51	31	280	152	87	9	4	82	50	7
2	3.1	11.6	320	73	420	2250	5.75	30.82	5.4	19	0	1	0.26	0	0.01	1	1	50	15	3	0	0	1	0	0
3	9.1	14.4	361	126	559	3216	4.44	25.52	5.8	53	15	13	0.42	0.19	0.10	2	0	78	19	8	0	0	1	0	0
4	21.0	24.5	242	44	63	486	1.43	11.05	7.7	24	8	7	0.55	0.18	0.16	1	0	19	0	0	0	0	0	0	0
5	28.6	29.1	320	81	109	929	1.35	11.47	8.5	44	16	14	0.54	0.20	0.17	2	0	31	3	0	0	0	0	0	0
6	29.8	29.8	210	37	12	155	0.32	4.19	12.9	30	14	13	0.81	0.38	0.35	1	0	5	0	0	0	0	0	0	0
7	37.2	37.2	525	209	42	496	0.20	2.37	11.8	189	107	107	0.90	0.51	0.51	0	0	11	1	0	0	0	0	0	0
8	42.5	42.5	334	53	8	142	0.15	2.68	17.8	47	25	24	0.89	0.47	0.47	1	0	2	0	0	0	0	0	0	0
9	47.6	47.6	411	88	9	137	0.10	1.56	15.2	80	55	53	0.91	0.63	0.63	2	0	3	0	0	0	0	0	0	0
10	50.1	50.1	177	22	2	27	0.09	1.23	13.5	20	15	15	1	0.68	0.68	0	0	0	0	0	0	0	0	0	0
11	62.7	62.7	158	13	0	17	0	1.31	—	13	9	9	1	0.69	0.69	0	0	0	0	0	0	0	0	0	0
12	63.7	63.7	134	7	0	8	0	1.14	—	7	5	5	1	0.71	0.71	0	0	0	0	0	0	0	0	0	0
13	72.6	72.6	241	16	0	7	0	0.44	—	16	15	15	1	0.94	0.94	0	0	0	0	0	0	0	0	0	0
14	92.9	92.9	225	17	0	11	0	0.65	—	17	10	10	1	0.59	0.59	0	0	0	0	0	0	0	0	0	0
15	98.7	98.7	31	5	0	4	0	0.80	—	5	4	4	1	0.80	0.80	0	0	0	0	0	0	0	0	0	0
16	104.7	104.7	78	3	0	0	0	0	—	3	3	3	1	1	1	0	0	0	0	0	0	0	0	0	0
17	119	119	173	10	0	9	0	0.90	—	10	6	6	1	0.60	0.60	0	0	0	0	0	0	0	0	0	0
18	122	122	117	9	1	2	0.11	0.22	—	8	7	6	0.89	0.78	0.67	1	0	0	0	0	0	0	0	0	0
19	130	130	182	12	0	0	0	0	—	12	12	12	1	1	1	0	0	0	0	0	0	0	0	0	0
20	150	150	139	5	0	0	0	0	—	5	5	5	1	1	1	0	0	0	0	0	0	0	0	0	0
21	156	156	68	1	0	1	0	1	—	1	0	0	1	—	—	0	0	0	0	0	0	0	0	0	0
22	214	214	131	15	0	3	0	0.23	—	13	13	13	1	1	1	0	0	0	0	0	0	0	0	0	0
23	216	216	96	5	0	0	0	0	—	5	5	5	1	1	1	0	0	0	0	0	0	0	0	0	0
24	230	230	95	4	0	0	0	0	—	4	4	4	1	1	1	0	0	0	0	0	0	0	0	0	0
25	235	235	55	6	0	0	0	0	—	6	6	6	1	1	1	0	0	0	0	0	0	0	0	0	0
26	306	306	33	4	0	0	0	0	—	4	4	4	1	1	1	0	0	0	0	0	0	0	0	0	0
27	325	325	66	3	0	0	0	0	—	3	3	3	1	1	1	0	0	0	0	0	0	0	0	0	0
0	—	—	0	1677	104	502	0.06	0.34	—	1599	1507	1471	—	—	—	36	0	7	0	0	0	0	0	0	0

3. Results

The essential features that come out of table 1 could be summarised as follows:-

(1) Out of the 2905 three-hour periods available for analysis, one or more of the observing stations reported T during 1228 three-hour periods. During each of these 1228 periods, there would be a closest station reporting T. This is referred to as CS. Column 5 gives the number of occasions when each station was CS.

(2) The average number of counts registered per three-hour period, when each observing station was CS, by the VO3 and VO4 respectively are shown in columns 8 and 9. It will be noticed that there is a sharp drop in the counting rate of both counters when CS shifts from station 1 to 2, which appears to indicate that there is a short range signal of range less than 11.6km from thunderstorms, to which both counters are sensitive. Column 17 seems to suggest that the VO3 is more sensitive to this short range signal than the VO4. Columns 24, 25 and 26 also bring out the existence of a short range signal of range less than the effective distance of of station 2 from station 1.

(3) Column 8 indicates that the counting range of the VO3 for the longer range signal is not more than 50km and that the counting efficiency for this signal drops sharply at about 15km range.

(4) Column 9 indicates that the counting efficiency of the VO4 to the longer range signal drops off more gradually than the efficiency of the VO3. There appears to be a drop in efficiency between about 15km and 30km range.

(5) Columns 14 and 15 give the fraction of three-hour periods when a station was CS and there were zero counts recorded in the VO3 and VO4 respectively. From these columns it is clear that the VO3 does not register any counts from lightning beyond 50km and that the maximum range of the VO4 is in the region of 80 to 100 km.

(6) The ratio of counts VO4/VO3 when each station is CS is given in column 10. It is seen that on an average the VO4 counts more than the VO3. The ratio VO4/VO3 is seen to increase as the CS recedes from Colombo.

(7) Columns 17 and 18 show that on some occasions the VO3 registered more counts than the VO4, but that this phenomenon happens almost exclusively when station 1 is CS. This observation seems to point out to the fact that the short range signal from thunderstorms referred to in (2) above begins to trigger the VO3 at a range which is a little larger than the triggering range for the VO4.

We have interpreted the long range signal to be due to cloud to ground flashes and the short range signal as being due to intra-cloud flashes. The basis for this interpretation will be discussed later.

In interpreting table 1, another factor has to be kept in mind. The counts are taken on a three-hourly basis. During this time period thunderstorms are not stationary. Meteorological observations in Sri Lanka suggest that thunderstorms would move an average distance of about 45km towards or away from Colombo during a three-hour period. Also thunderstorms in Sri Lanka are not of the frontal type but thermal and wind confluence storms which are generated more or less in isolated areas and not on a broad front. Thus in working out the counting efficiencies of the counters as a function of distance from table 1, one has to assume that the counts registered in a given three-hour period are due to storms approaching or receding from Colombo on a relatively narrow front.

4. Deduction of the Counting Efficiencies of the Counters as a function of distance of the Thunderstorm

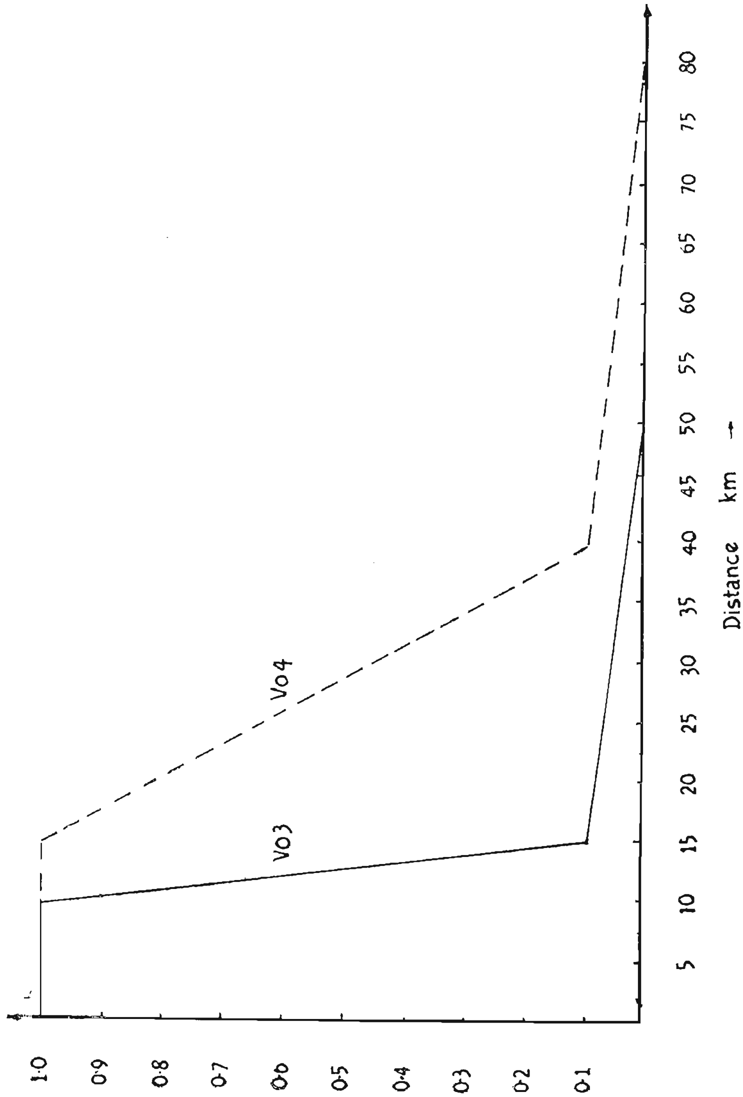
We shall assume that the counts registered per three-hour period when a station is CS comes from thunderstorms at distances ranging from the effective distance of the station from Colombo to a distance of 45km beyond this effective distance.

Hence if the effective distance of a station is X km, then the average number of counts registered per three-hour period by a counter when that station was CS must be proportional to the area of the efficiency versus distance curve of that counter lying between distances of X km and (X + 45) km.

To avoid confusion we shall first concentrate on the long range signal and assume that all the counts registered when stations 2 to 27 are CS are due to this long range signal which come from cloud to ground lightning flashes.

Figure 2 shows the counting efficiency curves we have deduced for the VO3 and the VO4 for these signals. In table 1, it is seen that when the CS is at an effective distance of 11.6 km, the VO3 counting rate per three-hour period averaged over the year is 5.75. On the basis of the procedure described at the beginning of this section, the counting rates per three-hour period can be worked out for the VO3 and VO4 as a function of the distance of the CS by standardising the VO3 count at a CS distance of 11.6 km to 5.75. Due to the shorter range of the VO3 it was considered that there was less ambiguity in the VO3 counts and that standardisation to an experimental value of the VO3 was preferable to standardising to an experimental count of the VO4. Actually it is found that there is little difference if the experimental VO4 count at 11.6 km is taken for standardisation instead.

Figures 3(a) and 3(b) are counting rate curves worked out using this procedure. The experimental values are also marked and it would appear that the efficiency curves shown in Figure 2 have been chosen satisfactorily.



Counting Efficiency —

Figure 2. Counting efficiencies for cloud to ground flashes

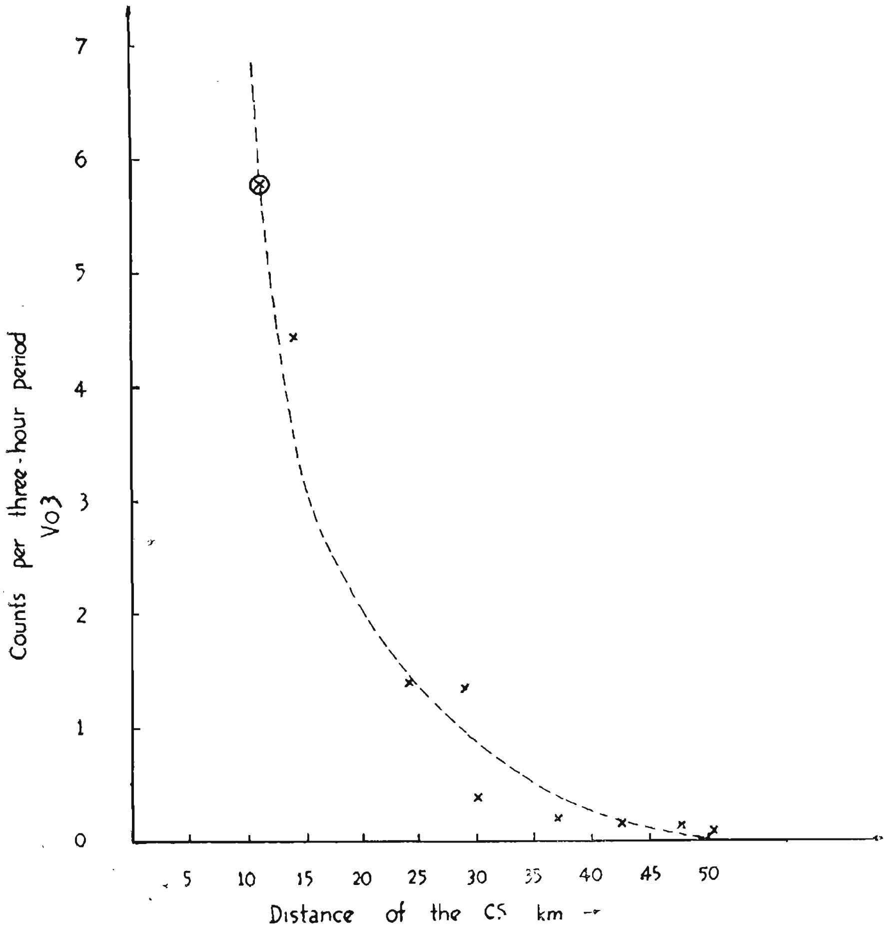


Figure 3 (a). Experimental data of VO3 counts compared with counts expected from the efficiency curve of the VO3 in figure 2.

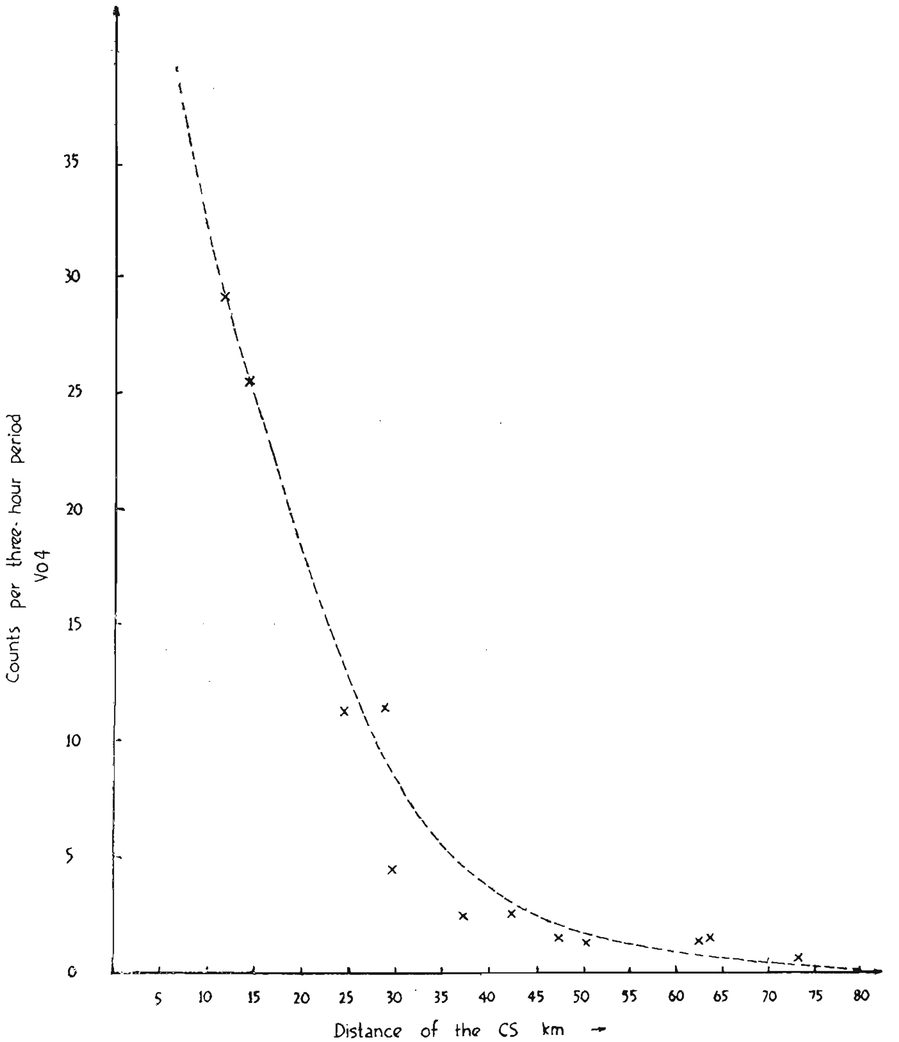


Figure 3 (b). Experimental data of VO4 counts compared with counts expected from the efficiency curve of the VO4 in figure 2.

When station 1 is the CS, it is assumed that both cloud to ground flashes and intra-cloud flashes trigger the counters. The possibility of the counters registering spurious counts under conditions of high ambient electric fields present in the close proximity of charged clouds is dealt with later.

From columns 5, 6 and 7 of table 1, it will be seen that over the year there were 360 three-hour periods when station 1 was the CS and that during these periods 21948 and 30789 counts respectively were registered on the VO3 and VO4. It has to be estimated how many of these counts are due to cloud to ground strokes.

The average effective distance of the closest approach of a thunderstorm when the CS is 1 was taken to be 6.67km. Extrapolating the curves of figure 3 to this distance, yields average counting rates per three-hour period of 14.4 and 42.4 respectively for the VO3 and VO4. In the 360 three-hour periods when station 1 was the CS, it is therefore estimated that 5184 and 15264 counts respectively on the VO3 and VO4 were due to cloud to ground flashes. This means that during the year the VO3 registered 16764 counts due to intra-cloud flashes and the VO4 registered 15525 counts. The VO3 counts only slightly more intra-cloud flashes than the VO4, which means that the effective range of the VO3 for intra-cloud flashes is only slightly bigger than the range of the VO4.

According to the counting efficiency curves for cloud to ground flashes deduced in Figure 2, both counters register all ground flashes that take place within 10km of the counters. When the CS is 1, we considered that the average closest distance of approach of a thunderstorm is 6.67km. Then on an average, on our assumptions during a three-hour period when the CS is 1, thunderstorms should occur between 6.67km and 51.67km from the counters, and out of the 5184 and 15264 cloud to ground flashes registered by the VO3 and VO4 respectively during the 360 three-hour periods when the CS was station 1, the numbers of cloud to ground flashes that must have occurred beyond 10km from the counters should be proportional to the areas under the respective counting efficiency curves between 10km and 51.67km. These areas are in the ratio of 9:39.5 for the VO3 and VO4, whence it is easily deduced that there were 2134 cloud to ground flashes within 10km of the counters during the year.

5. The Electrical Characteristics of the Counters

Both counters use identical antennae. A voltage $V_i(t)$ picked up by the antenna is first fed into a filter circuit and the output $V_0(t)$ from the filter is fed into the base of a 2N914 transistor. If $V_0(t)$ exceeds + A volt, there is a count. A is the same for both counters and is about 0.58 Volt. The circuitry ensures that there is a dead time of 1 second after a count.

The antenna filter circuit of both counters can be represented by an equivalent circuit of the type shown in Figure 4. In this circuit, if $V_i(t) = V \cos\omega t$, $V_0(t)$ is a sinusoidal voltage of amplitude V_0 given by:-

$$V_0 = \frac{\omega}{\{(\omega^2 + \alpha^2)(\omega^2 + \beta^2)\}^{\frac{1}{2}}} \, \frac{V}{rC},$$

$$\text{where } \alpha\beta = \frac{1}{rCRC_a} \quad \text{and} \quad (\alpha + \beta) = \frac{1}{rC}\left\{1 + \frac{r}{R} + \frac{C}{C_a}\right\}$$

The frequency response is characterised by:

(*a*) V_0 is a maximum at $\omega = \omega_0 = (\alpha\beta)^{\frac{1}{2}}$ and

(*b*) V_0 is the same for $\omega = n\omega$, and $\omega = \omega_0/n$ where n is any positive number.

In the VO3, $\omega_0 = 2\pi \times 500$, and in the VO4, $\omega_0 = 2\pi \times 10{,}000$. Also in both counters $V_0 = \frac{10}{17} (V_0)_{max}$ when $\omega = 5\omega_0$ and when $\omega = \omega_0/5$.

The threshold of counting for a sinusoidal signal for both counters was adjusted for $V = 15.1$ Volt at $\omega = \omega_0$.

The effective height of the vertical antenna was measured by Kannangara et al[8] and found to be 1.88m. By this it is understood that in a vertical electric field of E Volt m^{-1} directed downwards the antenna acquires a potential of 1.88E volt relative to earth.

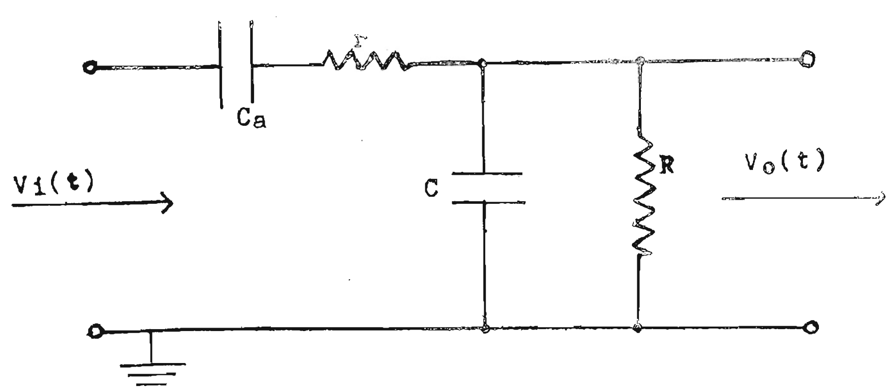


Figure 4. Equivalent circuit of the antenna and filter.

To ascertain the response of the counters to lightning, it is convenient to idealise the voltage change V_i (t) fed into the antenna to a ramp change of the type shown in Figure 5. The two counters respond to the same V if $\omega_0 t_m$ is the same. Since ω_0 differs by a factor 20 in both counters, the two counters respond differently for a given t_m. It is in terms of this difference that we have interpreted the counting data.

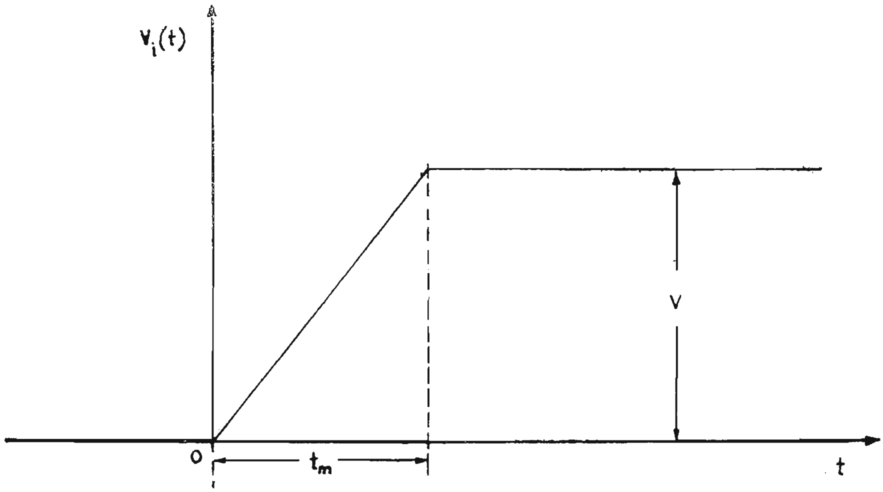


Figure 5. Idealised electrostatic voltage change fed into a counter of a lightning discharge

A circuit analysis indicates that when $t_m = 0$, that is, for a step voltage change of V volts, both counters are triggered when V exceeds roughly 17.7 Volt. This threshold voltage remains practically unchanged up to $\omega_0 t_m = 1$, which corresponds to $t_m = 260 \mu s$ for the VO3 and $t_m = 13 \mu s$ for the VO4. For t_m larger than these values, higher values of V are needed to trigger the counters. Table 2 indicates some rough values of V needed to trigger the counter for various values of t_m from 0 to 1 ms.

TABLE 2.

	Triggering Voltage V	
$t_m \mu s$	VO3	VO4
0	17.7	17.7
16	17.7	17.7
60	17.7	22
100	17.7	38
200	17.7	60
500	19	114
1000	26	180

Another important point that comes out in the circuit analysis is that for an input step voltage, V_o (t) reaches a maximum at $t = 320\mu s$ in the VO3 and $t = 16\mu s$ in the VO4. This means that an input voltage pulse with a rise time of t_m, a plateau extending up to time t_p, and subsequent decay, in any manner, will be seen effectively as a step voltage change if t_p is greater than $16\mu s$ by the VO4. In the case of the VO3, t_p must be greater than $320\mu s$. Also it will be clear that the VO3 will be quite insensitive to a voltage pulse with $t_p << 360\mu s$. For the VO4 to be insensitive, t_p must be $<< 16\mu s$.

6. Field changes produced by Lightning Discharges

An intra-cloud discharge essentially neutralises an electric dipole above ground and a cloud to ground discharge essentially neutralises a pocket charge above ground. The electrostatic field change, due to both these types of discharge, at a point near the earth's surface at a horizontal distance D from the discharge can be idealised to a ramp pulse of the type considered in section 5.

In the case of a cloud to ground flash bringing down negative charge, the field change will always be positive (a vertical field directed into the earth is conventionally called positive.)

The electrical dipole neutralised in an intra-cloud discharge, usually has its negative charge nearer the earth's surface. The electric field at the earth's surface due to such a dipole is vertical and there is a neutral point at some horizontal distance D_n from the dipole where the field undergoes a change in sign. At distances within D_n the electrostatic field change resulting from a discharge is positive whereas beyond D_n the change is negative. Thus the counters have to be within D_n to be triggered by an intra-cloud flash. For the purpose of this analysis we shall consider an intra-cloud discharge to be represented by the discharge of a vertical dipole with its negative charge at a height h_1 km and the positive charge at a height h_2 km with $h_2 > h_1$. The horizontal distance on the earth's surface from the dipole where field inversion takes place is $D_n = h_1^{1/3} h_2^{1/3} (h_1^{2/3} + h_2^{2/3})^{1/2}$. In cloud physics, it is commonly believed that the negative charge in a cloud concentrates at an altitude near the $-10°C$ isothermal level and the positive charge is centred near the $-30°C$ isothermal level. In the tropics, these isothermals are at altitudes of 5km and 10km roughly. Thus substituting $h_1 = 5$km and $h_2 = 10$km, in the tropics we could expect D_n to be 10km. Hence our assumption that the counters register intra-cloud flashes only when station 1 is the CS is reasonable.

In a cloud to ground flash, due to the dead time of 1 second after a count, field changes produced by the first return stroke only will be of importance.

Essentially, the first return stroke discharges to earth the charge deposited on the stepped leader. We can idealise this as the discharge of a point negative charge Q to earth from some height H. The value of H will depend on the distribution of negative charge deposited on the stepped leader.

The electrostatic field change at the earth's surface at a horizontal distance D would be given by:-

$$E = \frac{18 \times 10^3 \times QH}{(H^2 + D^2)^{3/2}} \text{ Volt m}^{-1}$$

where Q is in Coulomb, and H and D are in km.

The time taken for the discharge would be roughly the time for the potential wave of the first return stroke to travel up the leader channel from the ground to the cloud. Values of about $8 \times 10^7 \text{m.s}^{-1}$ are usually assumed for the velocity of the potential wave, and in the tropics the length of the channel is usually taken to be of the order of 5km. This gives a time of about $60\mu s$ for the discharge. The electrostatic field change produced by the discharge could thus be approximated to a ramp pulse with $t_m \sim 60s$. From table 2, VO3 will need field change of $\frac{17.7}{1.88} = 9.4 \text{ Volt m}^{-1}$ to be triggered and the VO4 a slightly higher field change. Thus the VO3 is more sensitive to the electrostatic field change of the first return ground stroke of a cloud to ground flash than the VO4. But very large currents develop in the first return stroke in times of the order of a few μs and the large rates of change of current in the lightning channel travelling up for times of the order of $60\mu s$ produce radiation field pulses with rise times t_m of the order of 3 or 4 μs and plateau times t_p of the order of $60\mu s$. The VO3 is quite insensitive to these pulses but the VO4 will see them like a step voltage change and can be triggered by them.

The VO3 can be triggered only by the electrostatic field change. The experimentally deduced counting efficiency curves of figure 2 suggest that all cloud to ground strokes are registered by the VO3 up to a distance of 10km. Hence experiment suggests that :-

$$\frac{QH}{(H^2 + 100)^{3/2}} > \frac{9.4}{18 \times 10^3} = 0.52 \times 10^{-3}$$

Assuming a leader length of 5km, and assuming a uniform charge distribution on the leader, the value of H should be 2.5km.[13] Using this value for H we obtain a lower limit of Q of 0.23 Coulomb. However Berger et al[2] have suggested that 95 percent of first return strokes bring down more than 1.1 C of negative charge. 50 percent more than 4.5C and 5 percent more than 20C. If these values are extrapolated, it suggests that all first return ground strokes bring down more than 0.8C, If we use this as the minimum value of Q then our results suggest that $H = 0.65$km which means the charge deposited on the leader is heavily concentrated at the lower end. This agrees with the stand taken by Bruce and Golde,[5] which is physically more realistic.

Our results indicate that the range of the VO3 for ground strokes is not more than 50km. Assuming that $H = 0.65$km this gives Q not more than 100C.

The curves of figure 2 suggest that the VO4 counts all cloud to ground flashes up to a distance of 15km. It would be the radiation field pulse that triggers the VO4. The radiation field drops off inversely as the distance and could be represented by $E_R = \frac{X}{D}$. If E_R exceeds 9.4 Volt m^{-1} the VO4 should register a count. Taking D as 15km we then deduce that the radiation field of all cloud to ground first return strokes must satisfy $E_R > \frac{141.5}{D}$ Vm^{-1}.

The calculations of Uman *et al*[14] indicate that in the expression $E_R = \frac{X}{D}$, X is directly proportional to vI_p where v is the velocity of ascent of the current pulse and I_p is the peak current in the current pulse. For $vI_p = 8 \times 10^8$ $m.s^{-1}kA$ they obtained $X = 175$. Assuming the rough validity of Uman's calculations our experimental value suggests that all lightning first return strokes have $vI_p > 6.5 \times 10^8$ ms^{-1} kA. If we then assume a commonly accepted value of $v = 8 \times 10^7 m.s^{-1}$ our results indicate, on the basis of Uman's calculations, that all first return strokes have an $I_p > 6.5$kA.

Berger *et al*[10] estimated that 95 percent of first return strokes have $I_p > 14$kA, 50 percent > 30kA and 5 percent > 80kA. If these values are extrapolated to 100 percent, they also indicate that all cloud to ground first return strokes should have $I_p > 6.5$kA.

Experimental evidence regarding intra-cloud lightning is vague. Brook and Ogawa[4] summarised as best as possible the existing situation.

An intra-cloud discharge appears to consist of a main streamer, which is similar to the leader of a cloud to ground stroke, in which currents of the order of 120A flow for about 250ms neutralising about 30C of charge. Superposed on this streamer there appear to be short duration bursts of current lasting a period of about 1ms, where on the average, about 1.4C of charge are neutralised. More recently Rustam *et al*[12], have suggested that these bursts could be stronger, neutralising about 2.4C of charge and leading to a mean dipole moment change of about 13C km, implying that the dipole length is of the order of 5.6km. There is no indication of the sort of current involved in this paper.

From our analysis it will be seen that only the short current bursts in intra-cloud flashes can trigger the counters through the electrostatic field changes they produce.

Suppose such a burst of current neutralises a dipole of charge Q with the negative charge at an altitude of h_1 km and the positive charge at a height of $h_2$km. We shall consider a representative vertical dipole. The counters can be triggered only by a positive field change and hence, as was pointed out earlier, the counters have to be within a horizontal distance of $h_1^{1/3} h_2^{1/3}(h_1^{2/3} + h_2^{2/3})^{1/2}$km to be triggered. We interpret the short range force which comes from our experimental results to be due to the electrostatic field changer produced by the short period current bursts in an intra-cloud lightning flash occuring within this distance. Our observations indicate that this distance is not more than about 10km.

Q coulombs of charge neutralised in a vertical dipole with the negative and positive charge at a height of h_1 and h_2 km respectively produce a field change at a horizontal distance D given by:

$$E = 18 \times 10^3 \times Q \left\{ \frac{h_1}{(h_1^2 + D^2)^{3/2}} - \frac{h_2}{(h_2^2 + D^2)^{3/2}} \right\} \text{Volt m}^{-1}$$

Let us assume that Q = 1.4 Coulomb as reported by Brook and Ogawa.[4] If the time taken for the discharge is 1ms then the counters will see the field change as a ramp with t_m = 1ms. If the change is positive and greater than 26/1.88 volt m^{-1} the VO3 counter will register a count. If we put h_1 = 5km and h_2 = 10km, then with Q = 1.4C, the distance D at which the VO3 starts counting works out as 9.2km, which fits in well with our experimental observations. On the other hand the VO4 will register only if the field changes is greater than 180/1.88 volt m^{-1} and would give a range of ~ 6. 2km for the VO4. This would imply that the VO4 would count only 45 percent of the intra-cloud strokes counted by the VO3. This does not fit in with our observations.

However if we take t_m to be ~ 200 μs, then the counting range of the VO4 for intra-cloud strokes goes up to 8.1 km,and it will count 78 percent of the intra-cloud strokes counted by the VO3.

If we take Q = 2.4C as suggested by Rustam *et al*, then with t_m = 200 μs, the VO3 range for intra-cloud flashes works out to be 9.5km and the VO4 range 8.7km. This implies that the VO4 will count nearly 84 percent of the intra-cloud flashes counted by the VO3 and would agree with our experimental results better.

Our results therefore appear to suggest that larger quantities of electricity flow for shorter durations of time in the current bursts that occur in intra-cloud lightning than are usually thought to exist.

7. Discussion

One of us (Kannangara) when working in South Sweden in the summer of 1978 observed the VO3 start counting continuously at its maximum counting rate of 1 per second when the level of the electric field exceeded $5000kVm^{-1}$ in the presence of precipitation. Such spurious counts were not observed on the VO4. A Japanese team working in North Sweden in Kiruna, too, observed spurious counts when the general electric field was high. We were well aware of the possibility of such spurious counts and kept a vigilant look out for them. Especially, the possibility that the sudden increase of the VO3 counting rate over that of the VO4 over short distances where a storm is a few kilometers away, may be caused by spurious counts was looked into. This effect was present both in rain and sunshine. Also, during a good part of the experiment it was possible to have a duplicate pair of counters operating at a site about a 100m away from the experimental pair.

For certain administrative reasons, it was not possible to take three hourly readings from both sets of counters all the time, but whenever simultaneous readings were taken, both sets agreed to within 5 percent under all conditions. We are of the opinion that spurious counts on the counters under tropical conditions, where the air is generally humid and electrostatic phenomena are difficult to generate, are minimal and do not affect the conclusions we have reached.

We have used the equivalent circuit shown in figure 4 for the analysis. In the Pisler circuit the output $V_0(t)$ is fed into the base of a 2N914 transistor. This introduces an extra degree of freedom which makes the actual Pisler circuit slightly different from the ideal equivalent circuit. A circuit analysis shows that the main difference between the ideal circuit and the Pisler circuit is that in the ideal circuit if V_i (t) is a linearly increasing voltage given by $V_i(t) = at$, then V_0 (t) reaches an asymptotic maximum at $t = \infty$, whereas in the Pisler circuit V_0 (t) reaches a maximum at $t \sim 5.7ms$. Apart from this difference, the circuit analysis indicates that the response of the Pisler circuit differs from that of the equivalent circuit by less than 10 percent for all the pulses we have considered. The nature of the present experiment does not warrant a distinction to be made between the two circuits.

It was pointed out in section 5 that our counting data indicate that over the year about 17000 intra-cloud strokes are counted. Our analysis shows that these counts should come from intra-cloud strokes within about 10km from the counters. In section 4 it was estimated that about 2000 ground flashes occurred within 10km from the counters. The ratio of intra-cloud flashes to ground flashes that comes out of our work is therefore roughly

$$\frac{17000}{2000} = 8.5$$

It is possible that there are a number of intra-cloud flashes which do not have sufficently sharp current bursts to trigger the counters. Eye estimates of thunderstorms in Sri Lanka seem to indicate that there are more than ten times as many intracloud flashes as cloud to ground flashes.

8. Conclusions

(*a*) During the year 1st March 1979 to 29th February 1980, there were 2134 cloud to ground flashes within a radius of 10 km from the counters which were installed in Colombo, Sri Lanka, which is 7°N of the Geographic Equator and 3°S of the Geomagnetic Equator. That is, the number of cloud to ground flashes per km^2 per year ~ 0.65.

(*b*) The Centre of charge brought down by the leader of a first return ground stroke is at an altitude of about 0.65 km, which means that the charge is heavily concentrated towards the lower end of the leader.

(*c*) The number of intra-cloud flashes strong enough to trigger the counters is about 8.5 times the number of cloud to ground flashes.

(*d*) Current bursts in intra-cloud flashes appear to be stronger and sharper than usually imagined.

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