Electrical Engineering in Japan, Vol. 99, No. 5, 1979
Translated from Denki Gakkai Ronbunshi, Vol. 99A, No. 9, September 1979, pp. 411-418

Characteristics of Discharge Current from a Needle Electrode and Its Application to Detection of a Thundercloud Approach

YOSHO HIGASHIYAMA, SABURO MUTO
Nagoya Institute of Technology
and
and KENJI HORI
Nagoya University

1. Introduction

Due to the improvement of observation techniques and the wide range of observation data, the mechanisms of development of thunderclouds and the process of charging and lightning discharge have gradually become clear [1, 2]. However, the observation of random lightning discharge is very difficult and the discharge mechanism has not been analyzed in detail. The natural lightning which strikes specific places such as high-rise buildings has been investigated for a long time at such locations as the Empire State Building in New York [3]. More recently, Berger et al. [4] performed observations at the radio communication tower at the top of Mt. San Salvatore in Switzerland. Further experiments in which artificial lightning was produced at a particular time and place were performed by Newman et al. in 1966 on the ocean off the coast of Florida by launching a rocket carrying a wire to thunderclouds. Subsequently, between 1967 and 1977, at Sant Privat D'Allier field in France, the same method was used to create artificial lightning by launching rockets 104 times. Sixty-five of 104 launches were successful in producing lightning and yielded much data about the current waveform at the time of the lightning, as well as pictures of the routes of discharges [6].

We attempted, but failed, to produce lightning using a rocket on the Iruka Ike coast in Inuyama City in July and August of 1977; however, in December of the same year, we were successful in producing lightning twice at the Kohoku-Gata reclaimed land in Nigata Prefecture. In these latter experiments, it was important to determine the timing of the launching of a rocket to increase the probability of the production of lightning; the rocket should be launched when thunderclouds approach directly above the experimental field and when the electric field on the ground becomes maximum. At present, a field mill is used widely for the determination of the electric field; however, this apparatus has some disadvantages: (1) to keep a shielded sector continuously revolving at high speed, a power source is required; (2) to avoid the disturbance of the surrounding electric field on the ground, a large space is required; (3) to obtain accurate measurements of the electric field, the detection surface has to be directed upward toward the sky, which is not convenient when it rains; (4) finally, it is expensive.

By contrast, in the method described in this paper, the ground electric field is obtained by measuring a corona current at a protruding needle above the ground. The advantages of this method are: (1) there are no moving parts and the structure is simple; when nonerosive metal is used for the electrode, endurance is enhanced; (2) since it uses the corona discharge phenomenon of an electric field under thunderclouds, the detection of thunderclouds is very reliable; (3) for the measurements of the corona current no external power source is required; (4) using the inexpensive device, multiple observations can easily be done.

In section 3, we will discuss the corona characteristics based on both simulated experimental results in the laboratory and the theoretical calculations. In section 4, we will describe the procedure of two successful experiments in 1977 in

ISSN0424-7760/79/0050-0001$07.50/0

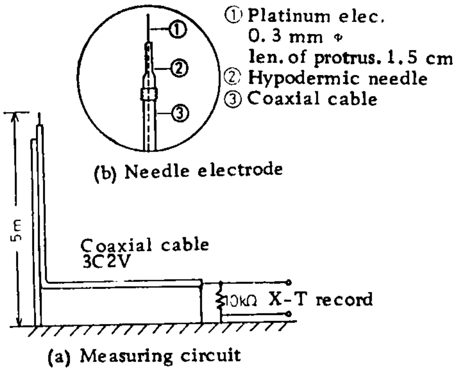


Fig. 1. Measuring system of point discharge current.

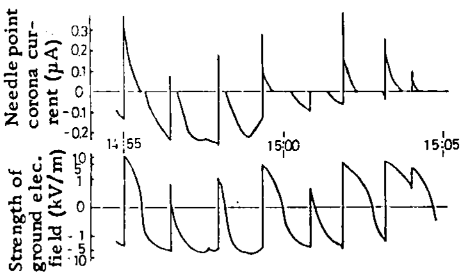


Fig. 2. An example of the point discharge current and the surface field strength under a thunderstrom.

the production of lightning by determining the timing of the launching of a rocket by our method. In the last section, we will summarize the important results obtained through this research.

2. Characteristics of the Point Discharge Current During Thunderstorm

2.1 Method of measurements

The measuring system of point discharge current is shown in Fig. 1 [7]. A platinum wire electrode whose curvature at the tip is 0.15 mm was used for the measurements of discharge current. As shown in Fig. 1 (a), the platinum wire was inserted through a hypodermic needle, exposing 1.5 cm, and the pole was set 5 m high. For the connection to the measuring instrument 10 m from the needle electrode, a coaxial cable (3C2V) was used. During the thunderstorm, since the ground electric field increased, the corona discharge was observed at the tip of the needle. The discharge current was fed through a 10-kΩ detection resistor and the potential difference across the resistor was measured by a voltmeter with a sensitivity of 1 mV/cm (0.1 μA/cm equivalent) and recorded. The chart speed of the recorder was 2 cm/min during the thunderstorm, and when severe, the speed was increased to 6 cm/min.

For the measurements of the electric field strength on the ground, a field mill (a ground electric field meter with a rotating cylinder) was used. The range of the measurements was from 0.1 to 0.2 kV/m in fine weather to ±20 kV/m or ±200 kV/m during the thunderstorm, and a system of two-step ranges was used. In these measurements, a range of ±20 kV/m was used, and the output voltage and the point corona discharge current were recorded simultaneously on a two-pen recorder. The advantage of this electric field meter is that it is usable in rainy weather even when the detection surface is kept upright.

2.2 Results of measurements

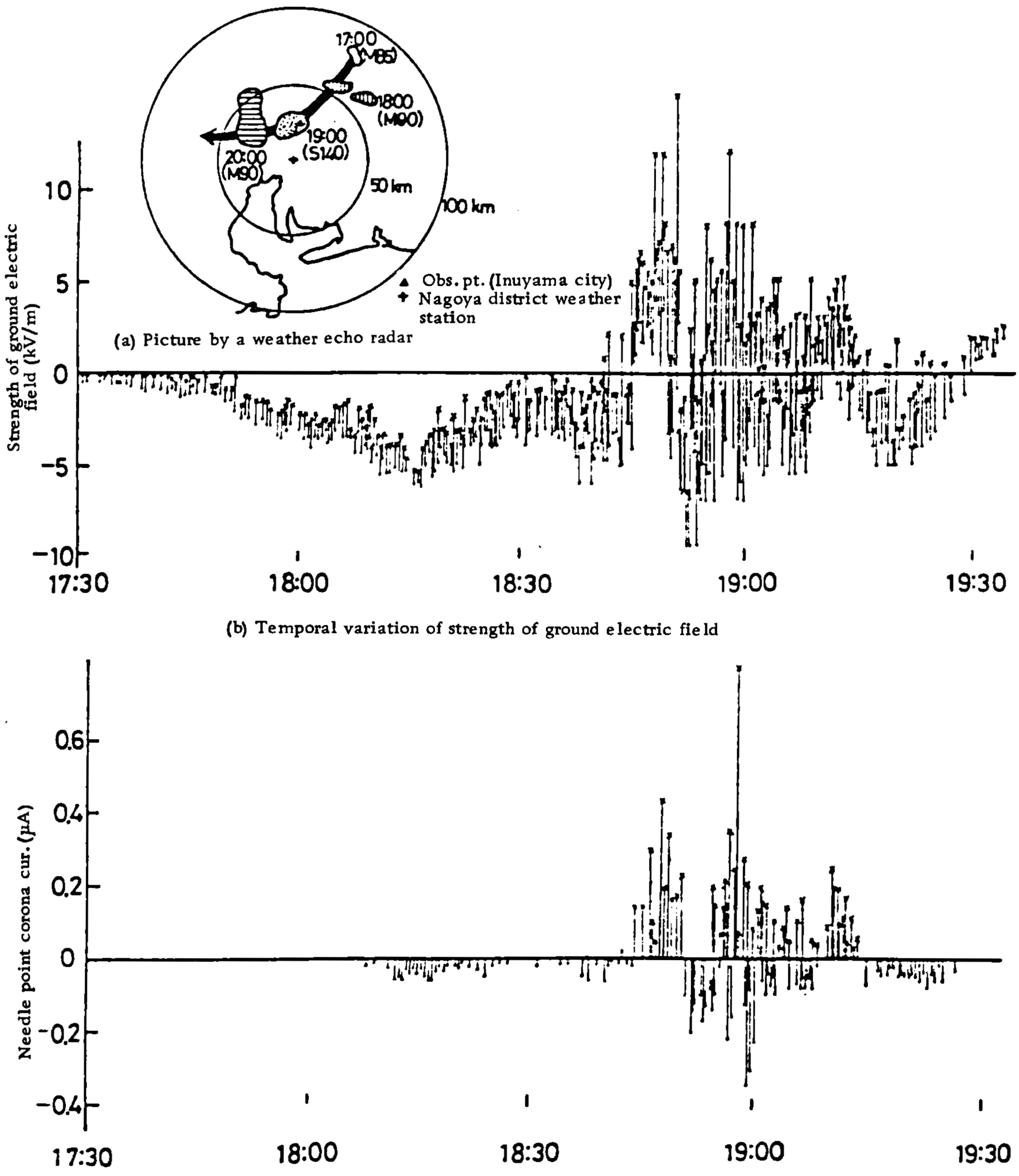
(1) Time sequence

An example of measurements of the point discharge corona current and the ground electric field strength in the case of lightning is shown in Fig. 2. When a thundercloud approaches, the electric field strength on the ground increases toward negative (polarity of the thunderclouds is negative). The ground electric field under the thundercloud reverses its polarity rapidly to positive after a strike. Then, due to the charge production mechanism of the thundercloud, the negative charges are produced on the bottom part of the thundercloud. The ground electric field again increases toward negative and this process is repeated.

The point discharge current changes corresponding to the ground electric field strength. We found that a threshold of the electric field exists at the initiation of the point discharge. This value was 1.5 kV/m in these experiments.

Measurements of the ground electric field strength and the temporal variation of the point discharge current for a 2-hour observation, when a thundercloud was passing above the observation point with discharge of several hundred times, are shown in Fig. 3; ● indicates the value immediately before abrupt changes and X indicates the value immediately after the change due to the discharge. These two points are connected by a straight line. Detailed variations within an interval of a few seconds were neglected and only major changes are shown. The appearance and disappearance of thunderclouds was observed by a weather radar at the Nagoya district weather station and the chart is shown in Fig. 3(a). In the figure, S and M represent the intensity of echo (heaviness of the rainfall by the radar, S denoting strong and M denoting moderate). The numbers on the chart represent the height of the echo or height of the thundercloud.

At about 16:00 on July 28, 1977, a thermal thunderstorm appeared near South Kiso in



(a) Picture by a weather echo radar

(b) Temporal variation of strength of ground electric field

(c) Temporal variation of needle point corona current

Fig. 3. Weather radar-echo, the time variation at the surface field strength and the point discharge current during a thunderstorm.

Nagano Prefecture, 60 km northeast of the observation point (Iruka Ike in Inuyama City) and moved southward at a speed of 30 km/h. The activity of the storm reached its peak at around 19:00 and passed above the observation point. The strength of the thundercloud deteriorated rapidly afterward.

According to the record of the ground electric field strength, abrupt small changes due to lightning discharges were observed and then the negative field strength immediately before discharges increased gradually. At around 18:40, the strength reached -6 kV/m. After this, the polarity of the ground field strength immediately before the discharge was reversed to positive. This polarity reversal may be due to the increasing influence of sparsely distributed positive charges on the bottom of the cloud. By 18:50, the negative field increased again and the maximum field strength immediately before the discharge became -10 kV/m; it increased over +10 kV/m

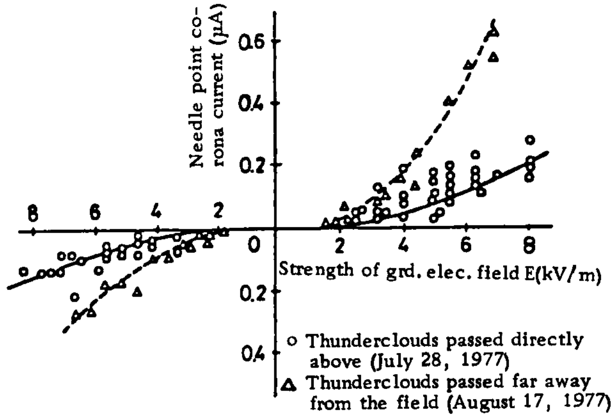


Fig. 4. The relation between the point discharge current and the surface field strength.

right after discharges. The activity became maximum and then rapidly decreased. Accompanied by changes in the ground electric field strength, the point corona current began to be recorded when the ground electric field strength exceeded 1.5 kV/m, and it became larger as the ground electric field increased. From 18:50 to 19:00 the electric field reached maximum; the current showed a change of -0.4 μA to +0.7 μA and then decreased gradually. At about 19:25, when the ground electric field fell below 2 kV/m, the corona current was not detectable. The measurements of the ground electric field strength and the point corona current show an obvious relationship and it has been shown clearly that the activity of thunderclouds and their time sequence can be determined by the variations of the corona current. This suggests the possibility of developing a lightning warning system by observing the point corona current.

(2) Correlation between the ground electric field strength and the point corona current

Figure 4 shows a relationship between the ground electric field strength E and the point corona current E-i. As in Fig. 2, Fig. 4 shows the values immediately before and after discharges; the positive direction of the current is identical to the direction of the current flow into the ground. The solid line represents the E-i characteristics of the thundercloud shown in Fig. 3 which passed directly above the observation point, and the dotted lines were obtained from the thundercloud which passed far away from the observation point on August 17 of the same year. These two lines are obtained by connecting the average values of the measurements. The difference in characteristics of two thunderclouds, one directly above and the other far away, depends on such weather conditions as wind, rain, and humidity. Among these, rain and humidity seem to exert the greatest influences on the corona current [8]. Although there is an obvious difference between the solid and dotted lines, in each case there is a clear correlation between the ground electric field strength and the point corona current. Whipple et al. [9] described this E-i relationship as

$$i = a(E^2 - E_0^2) \tag{1}$$

where E_0 is the strength of the ground electric field at the time of the initiation of the corona current, and a = const. Equation (1) does not include the effect of weather conditions. Chalmer [10] and Chapman [11] et al. described the corona current i in terms of the ground electric field E by considering the effect of the wind velocity. However, as shown in Fig. 4, the variation for the identical ground electric field strength is large, and the weather condition varies from day to day, so the E-i characteristics vary. In general, it is difficult to obtain a relationship between the magnitude of the point corona current and the ground electric field strength.

Attention must be given to the fact demonstrated in Fig. 4 that once the point corona current is started, the magnitude of the corona current may differ for the identical ground electric field strengths but the ground electric field strength at the time of the beginning of the corona is constant. This means that when the ground electric field reaches 1.5 kV/m, the electric field concentrates in the vicinity of the needle point and satisfies the conditions for the initiation of corona discharge. Determination of the ground electric field strength by the discharge initiation point rather than by the magnitude of the point corona current can give the ground electric field strength independent of weather conditions.

3. Characteristics of the Initiation of Point Corona Current in Simulated Laboratory Experiments

3.1 Electrode configuration

The ground electric field created by the charges of the thundercloud was simulated by a uniform electric field produced by parallel plate electrodes. A needle electrode for the measurement of the corona current, which normally protruded from the earth, was simulated by a needle electrode projecting through a hole in the bottom plate electrode. The electrode configurations are shown in Fig. 5.

The plate electrode is a 1-m square aluminum plate, and the periphery of the plate was given some curvature in order to reduce the distortion of the electric field at the center of the electrode. A sewing needle with a diameter of ρ = 0.15 mm and a platinum wire with the same diameter were used as the needle electrode.

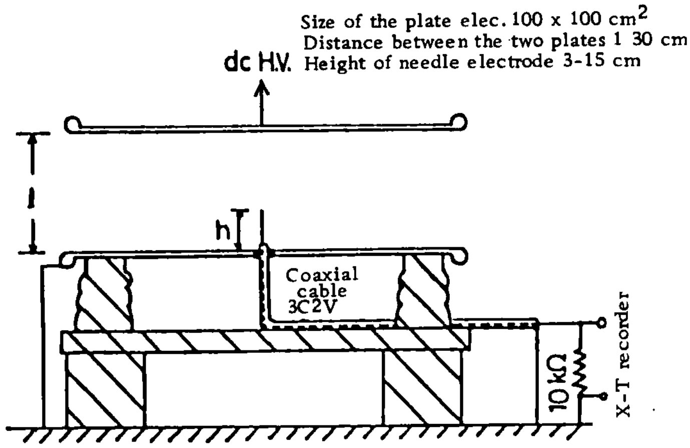


Fig. 5. Arrangement of experimental apparatus.

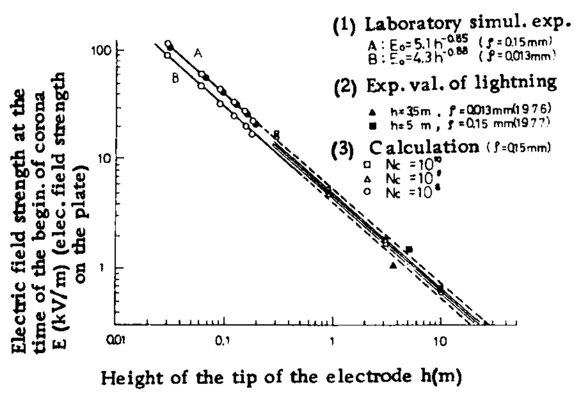


Fig. 6. The relation between and the height of needle electrode and the surface field strength at corona inception.

3.2 Experimental methods and results

We obtained the corona initiation voltage by changing the height of the needle electrode while maintaining a constant distance between the parallel plate electrodes. According to the result of the calculation of the static electric field by the method of finite elements, the electric field at a distance h directly above the needle electrode and at a distance h horizontally from the needle, was undisturbed by the existence of the needle electrode.

A positive or negative dc voltage was applied and gradually increased on the upper electrode. The corona current was measured by the method used in section 2.1. The corona initiation voltage was defined as the voltage which produces a continuous current. The magnitude of the current at this moment was in the order of 0.01μA. The electric field E_0 of the parallel electrodes at the moment of corona initiation was obtained from the applied voltage. The value E is equivalent to the ground electric field at the moment of the initiation of point corona discharge in the lightning experiment. The electric field strength of the parallel electrodes (uniform electric field) E_0 (kV/m) is shown against the height of the point electrode h(m) on a full logarithmic sheet. It will produce a straight line as shown in Fig. 6. Extrapolation of this result to the height of 10 m from the ground is shown by dotted lines in Fig. 6. When the results of two curvatures $\rho = 0.013$ mm and 0.15 mm, are compared, there was not much difference in the strengths of the ground field E_0, and it becomes clear that E_0 depends mainly on the height above the ground.

From Fig. 6, the relationship between E_0 and h can be written as follows:

$$E_0 = 4.3h^{-0.88}(\mathrm{kV/m}) \quad \rho = 0.013\mathrm{mm} \tag{2}$$

$$E_0 = 5.1h^{-0.85}(\mathrm{kV/m}) \quad \rho = 0.15\mathrm{mm} \tag{3}$$

Specifically, the electric field strength of the parallel electrodes (ground electric field strength) E_0 at the time of the corona discharge at the tip of the needle electrode is inversely proportional to 0.8 to 0.9 x h to the power of the height of the needle electrode from the ground.

We plotted the experimental value E_0 obtained by lightning measurements in Fig. 6; ▲ indicates the points for E_0 = 1 kV/m (1976) with h = 3.5 m and $\rho = 0.013$ mm; ■ indicates the points for E_0 = 1.5 kV/m (1977) with h = 5 m and $\rho = 0.15$ mm. These values agree roughly with the experimental values. Hence it is considered that Eqs. (2) and (3) are valid for the range of h = 10 m.

By using E_0-h characteristics, we can obtain the ground electric field at the time of corona discharge for the needle electrode of height h in advance. The use of multiple needle electrodes with different heights will enable us to make accurate measurements of the ground electric field strength.

Table 1. Comparison of experimental results E_0 with calculated values

Height of the tip h (m)	Strength of ground electric field at the beginning of corona E_0(kV/m)			
	calculated			read from experimental curves
	$N_c=10^8$	$N_c=10^9$	$N_c=10^{10}$	
10	0.6	0.63	0.65	0.7
3	1.6	1.7	1.8	2.0
0.9	4.6	4.8	5.1	5.6
0.3	15.4	16.1	16.8	15.0

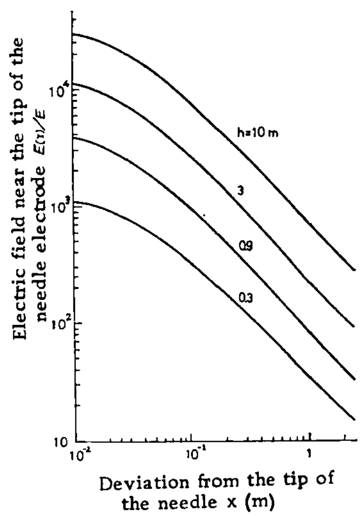


Fig. 7. Electric field strength near the tip of point calculated by finite element method.

3.3 Analysis of E_0-h characteristics

By calculating the electric field near the tip of the needle electrode via the method of finite elements, when a needle electrode was installed, we obtained the ground electric field strength at the moment when corona discharge started from the needle electrodes [12]. The electrode system used for the calculation had a needle electrode (with a semispherical tip of radius ρ and height h) between parallel electrodes. The plate distance was 100 m, $\rho = 0.15$ m, h = 0.3, 0.9, 3 and 1 m.

The representation of the ratio of the electric field near the tip of the needle electrode E(x) to uniform electric field E against h is shown in Fig. 7, where x is the distance (mm) from the axis of the needle electrode. Figure 7 indicates clearly that as the height of the tip of the needle electrode increases, the electric field strength at the tip of the needle electrode and near the needle electrode increased. By using this result, we obtained the uniform electric field strength (the ground electric field strength at the time of the initiation of the corona discharge E_0. As an equation for the condition of the initiation of corona discharge we used Eq. (4); this equation was derived by Takuma [13], and its usefulness is accepted:

$$\int_0^X (\alpha-\eta)\,dx=k \tag{4}$$

α is the ionization coefficient; η is the adhesive coefficient; X is a point where $\alpha = \eta$, k = const.

For the critical number of electrons, nc = e^k, where the electron avalanche changes into a streamer, we assumed 10^8, 10^9 and 10^{10}. The integration of Eq. (4) is represented by a quadratic Eq. (5) [13], which shows a relationship between $(\alpha - \eta)$ and electric field E_0 in the atmosphere with the values of α and η by Geballe:

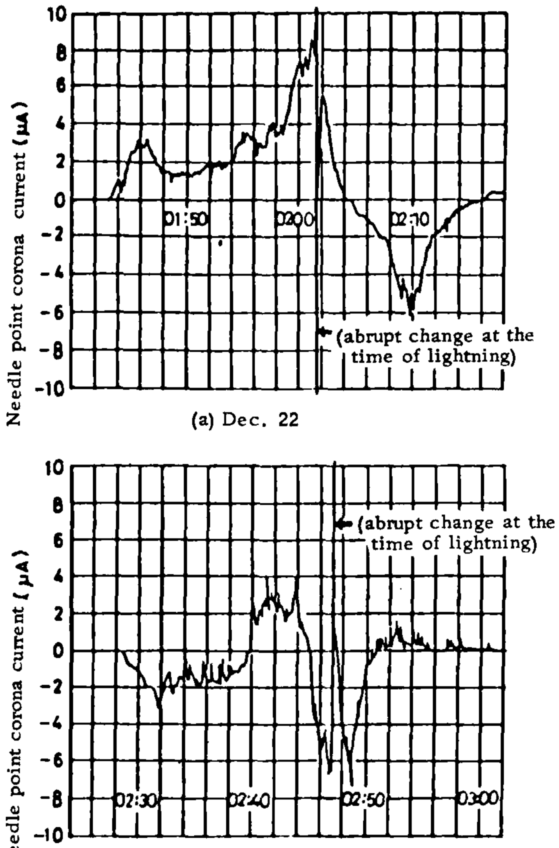
$$\alpha-\eta=2.1\times10^{-7}(E-2.4\times10^{4})^{2} \tag{5}$$

The uniform electric field E_0 satisfying Eq. (4) for various values of N_c, i.e., the result of the strength of the ground electric field at the time of initiation of corona discharge, was plotted in Fig. 6. Then we compared the results with extrapolated experimental values within an error of 20%.

4. Point Discharge Current in Lightning Flash Triggered by Rocket

4.1 Experimental results

We performed experiments and produced lightning with a wire-carrying rocket at Kitakata reclaimed land in Ishikawa Prefecture in December 1977 and succeeded twice in producing lightning. The timing for the firing of a rocket for these experiments was determined by the use of the characteristics of the point corona current.



(a) Dec. 22

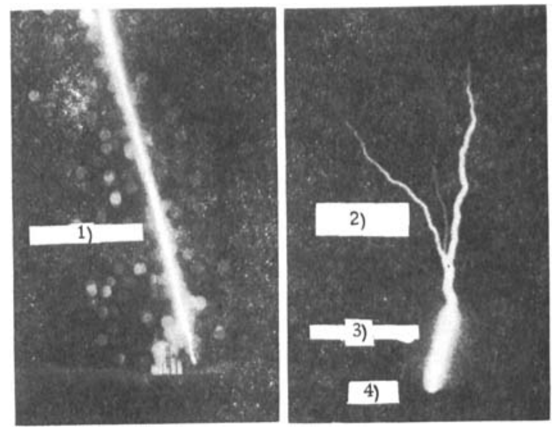
(b) Dec. 27

Fig. 8. The point discharge current at the time of triggering lightning.

Figure 8 shows changes in corona current at the time of the lightning bolt of a needle electrode (tip curvature 0.5 mm) placed at 5 m above the ground. At the reclaimed land site where a 100-V ac source was not available, we could not use a field mill.

Figure 8(a) shows a record at the time of the lightning on the 22nd of December. At about 1:40 a.m., a positive corona current started (the estimated strength of the electric field of the ground was 14 kV/m). Immediately after this, a rocket was fired and at the height of 78 m, a lightning flash was produced. The record of the corona current at the time of the strike shows that the recording pen went off the scale from positive to negative. This indicates that it was a positive discharge. The lightning current for this strike, as recorded by a steel magnetic piece, was 2200 A.

Figure 8(b) is a record for the triggering of lightning on December 27th. At 2:47, when the point corona current reached 8 μA, a rocket was fired and the triggering was made successfully at 153 m. The corona current at the time of triggering was -6.6 μA (estimated strength of the electric field was 11 kV/m). The change in the



(a) 110 cm from camera (b) 2500 m from camera (16 mm films)

1) Discharge along wire, 2) Upward discharge path; 3) Discharge along wire, 4) Ground surface

Fig. 9. Photographs of a lightning flash triggered by a rocket with steel wire.

point corona current indicates a negative lightning discharge; the lightning current was -1800 A. Figure 9 shows this lightning bolt; Fig. 9(a) is a picture taken 110 m from the lightning point and the lightning discharge can be seen clearly along the wire. Figure 9(b) is one frame of a 16 mm movie (24 frames/s) taken 2.5 m from the lightning site. Branches extending upward can easily be identified. The bright part of the lower part of the picture is a discharge along the wire.

4.2 Discussion of the results

From the preceding observations of several days at the experimental location before the firing of rockets, we found that the maximum point corona current will exceed 8 μA when a cloud which carried electron charges passes above the field. As described above, the magnitude of the point corona current is vulnerable to weather and other conditions, and it has a correlation with the ground electric field strength. Using the value 8 μA as the standard, we succeeded twice in triggering lightning.

The ground electric field strength was recorded at the base camp of the Space Charge Laboratory of Nagoya University, 5 km from the observation point of the corona current. Because of this distance, the ground electric field strength and the point corona current at the identical time cannot be correlated. However, from the weather radar we found that many clusters of the thundercloud passed continuously over the Kawakita Kata area; it is considered that the height and the charge of the thundercloud at the two points did not differ greatly. When the ground electric field strength reaches maximum, the point corona also reaches maximum. Therefore the distribution of the frequency of occurrence of the peaks of the ground electric field strength and of the point corona current statistically are almost identical. From this we obtained a relationship between the

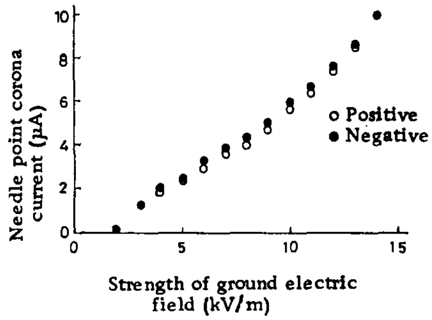


Fig. 10. The relation between the point discharge current and the field strength at Kahokugata.

point corona current and the ground electric field strength. From Fig. 10, at the time of launching of a rocket, the ground electric field strength was 14 kV/m for +10 μA, and -11 kV/m for -6.6 μA. These values are far larger than the value 6 kV/m which is considered to be the threshold for the initiation of lightning.

Thus by observing the initiation of the corona current flow from a needle electrode 5 m above the ground, we can detect the ground electric field above 1.5 kV/m and by observing the changes in the magnitude of the corona current, we can determine the timing for launching a rocket for the accurate triggering of lightning. To further increase the accuracy and dependability, by using the information obtained from multiple electrodes that corona current starts from the highest electrode to the lowest, we can study the time sequence of the increase in the ground electric field.

5. Conclusions

We studied the characteristics of the corona current during the thunderstorm with a needle electrode placed several meters above the ground. By comparing the current with the ground electric field and relating it to the movement of thunderclouds, we demonstrated the possibility of detecting a thundercloud and of determining the timing of launching of a rocket for the production of lightning flash. The summary of results is as follows.

1) During the thunderstorm, the temporal changes in the corona current from a needle electrode correspond to the changes in the ground electric field strength. Therefore, the movement of the thundercloud and the lightning discharge can be detected by observing the corona current using a needle electrode. We can apply these observations to the construction of a lightning warning system [15].

2) The needle corona current responds to the influence of weather conditions such as wind and rain, as well as to the ground electric field. The electric field strength at the time of the initiation of the needle corona current was constant independently of weather conditions.

3) According to the simulation experiments, the ground electric field strength E_0 at the time of initiation of the corona current flow to the needle electrode (a diameter $\rho = 0.15$ m and height h) is $E_0 = 5.1\ h^{-0.85}$. The validity of the empirical equation was confirmed by the analysis which included effects of electron avalanche to a streamer discharge.

4) A needle corona meter with multiple electrodes with different heights can be considered comparable to a field-mill ground electric field meter.

5) The needle corona current method is an easy and effective way to find the timing for the firing of a rocket to trigger lightning.

Acknowledgements

This research was supported partially by a grant from the Scientific Research Fund of the Ministry of Education in 1976-77.

We are grateful for the advice and help of Prof. Iwao Miyaji of Nagoya University, the principal investigator, Prof. Yoshikazu Ikeda at Chubu Institute of Technology, Mr. Shinchi Sumi, Mr. Fuminori Takeuchi at Nagoya University, Mr. Koichi Nakamura, Mr. Yutaka Okuda, Mr. Nobuyuki Kawamura at Nagoya Institute of Technology, Prof. Mitsugu Aeba at Kanazawa Institute of Technology, and our colleagues at the Educational Engineering Broadcast Center. We also owe thanks to Mr. Hisashi Yamashita, Mr. Aki Konishi, and Mr. Hiroyuki Naganawa of the University of Nagoya.

REFERENCES

1. M.A. Uman. Lightning (1969). McGraw-Hill Company.
2. R.H. Golde (Edited); Ibid. (1977) Academic Press.
3. J.H. Hagenguth and J.G. Anderson. Lightning to the Empire State Building, Part 111. Trans. Amer. Inst. Elect. Engrs., 71, pt. 3, 641 (1952).
4. K. Berger. Novel observation on lightning discharges: Results of research on Mount San Salvatore, J. Franklin Inst., 283, 478 (1967).
5. M.M. Newman, et al. Triggered lightning strokes at very close range, J. Geophys. Res., 72, 4761 (1967).
6. R.P. Fieux, et al. Research on artificial triggered lightning in France, IEEE Trans. Power Apparatus Syst., PAS-97, 725 (1978).
7. Higashiyama et al. Observation of lightning at Iruka Ike areas. Report IEE Tokai Branch Meeting 146, 1976.

8. Toriyama et al. High Voltage Engineering, Corona Publishing Co., p. 45, 1970.
9. J.J.W. Whipple and F.J. Scrase. Point discharge in the electric field of the earth, Geophys. Mem. Lond., 68, 1 (1936).
10. A. Chalmer. The relation of point dischrage current to potential difference and wind speed, J. Atmos. Terre. Phys., 24, 339 (1962).
11. S. Chapman. Corona point current in wind, J. Geophys. Res., 75, 2165 (1970).
12. Higashiyama et al. An analysis of ground electric field and needle point corona current by the method of finite elements during lightning, IEE Meeting Report, 971 (1978).
13. Takama. A discussion of the discharge mechanisms in air and the application for the calculation of flashover voltage in a gap, Jour. I.E.E., Japan, Vol. 91, 148 (Sept. 1971).
14. M.A. Harrison and R. Geballe. Simultaneous measurement of ionization and attachment coefficients, Phys. Rev., 91, 1 (1963).
15. Higashiyama et al. A relation between the ground electric field and needle point corona current in the production of lightning by rocket experiments, IEE Tokai Branch Meeting, 164 (1977).