LIGHTNING WARNING DEVICE WITH COMPLEX SENSORS AND ITS PERFORMANCE FOR ACTUAL THUNDERSTORMS

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Abstract. The authors designed and constructed a new lightning warning device with two different types of sensors. They have manufactured and sold the devices for several years under the name of "Coronarm". The one of them was installed at Honda Driving Plaza (a facility for the car race) in Kumamoto Prefecture, and all the issued warnings were recorded for one full year. The authors compared this record with the lightning activity records obtained at five meteorological institutions surrounding the device site, and examined the warning performance of the device. The result showed that the performance of the device was adequate.

1. Introduction

For the location of lightning discharges, the receptions of their electromagnetic radiation at multi-point stations are widely used. Several systems named LLP, LPATS and SAFIR have been developed, manufactured and are operated at various regions of the world. All these systems provide reliable information concerning the lightning activity. However, for the purpose of lightning warning at golf courses, recreation facilities etc., simple and less expensive devices are demanded. The authors designed a device for this purpose. They manufactured the device and sold it under the commercial name of Coronarm. The devices have been installed and used at numerous sites in Japan.

One device was installed at Honda Driving Plaza (a facility for the car race) in Kumamoto Prefecture. At this facility, they recorded all warning issues during one year from January 1, 1990 to December 31, 1990. The authors compared this record with the lightning activity observed at meteorological institutions surrounding the facility and analyzed the warning performance of the device.

2. Conventional lightning-warning apparatuses

The electric field-change ΔE [V/m] caused by a distant ground flash is represented by the following formula:

$$\Delta E = (1/4\pi\epsilon) \times (2hQ/r^3 + 2h/cr^2 \cdot dQ/dt + 2h/c^2r \cdot dQ^2/dt^2)$$

where h [m] is the height of charge center, r [m] is the horizontal distance of the flash and Q [C] is the amount of charge lowered to ground. The electric field-change ΔE [V/m] caused by a cloud discharge between vertically oriented positive and negative charges are also represented by the same formula, where h [m] is the distance between two charge centers. Here, c [m/s] and ϵ [F/m] represent the light velocity and dielectric constant of the air, respectively. The first, second and third terms in the formula are called static, inductive and radiation fields respectively. In the formula, the static field-changes predominate within distance of about 5 km from lightning discharges and the radiation field predominates at the

distance of about 30 km or farther. At the distance from 5 to 30 km, three terms contribute almost equally. With an antenna sensor of short time constant, mainly second and third terms are measured. With a field meter, all three terms and the electrostatic field caused by the cloud charge are simultaneously measured.

Most of the lightning-warning apparatuses measure above electric field changes. Several types of single-station lightning-warning apparatuses are commercially available. Flash counters, one of the types, are simple in structure but poor in storm-locating performance (Prentice, 1972). Other type apparatuses, using magnetic direction finders are rather expensive and not easy to operate (Pifer et al., 1991). A new attempt has been done to combine a photoelectric sensor with a field-change meter (Byerley III et al., 1992).

3. Relation between electric field and corona current

When the surface electric field reaches a certain value, corona discharges begin at sharp points of various objects on the ground surface and the corona current flows through the points. The corona current I is related with the surface electric field in the following equation:

$$I = a(E^2 - M^2)$$

where "a" and "M" are constants figured out by the shape and the height of the point (Chalmers, 1967, p.250). Because of this relationship, one can measure the surface electric field by measuring the corona current through a sharp point on the ground. The authors adopted this method to measure the surface electric field.

4. The design of the present warning device "Coronarm"

Since each type of conventional warning apparatus has its own merit and demerit, the authors constructed a new warning device, using an antenna sensor and an electric field meter simultaneously. To measure the electric field, they used a corona-current measuring method. Fig. 1 shows the photograph of the combined sensors. The metal hemisphere works as an antenna sensor and the 30 needles work as corona discharge points. Five metal cylinders are installed radially on the metal hemisphere and at each top a small metal ball is fixed, being separated by a short insulator cylinder. Each insulator is shaped so that rain water does not spoil the insulation. On a metal ball, six needles are detachably fixed, where medical injection needles are used because of their easy availability. The whole sensor system is installed at certain height above the ground or on the flat roof of a building, being supported by a metal pole.

Fig. 1 Photograph of a combined sensor

Fig. 2 shows the block diagram of the new warning device and illustrates how the

Fig. 2 Block diagram of warning device

signals from the sensors are dealt with and the warning signals are issued. The field-change detecting circuit is a VHF pulse counter which detects the field-change larger than about 500 V/m and outputs the ON signal when the counts per minute reach a preset value. The sensitivity of the circuit is manually changeable over 30 DB. The electric field detecting circuit also detects the electric field larger than about 500 V/m at its highest sensitivity.

According to the input of the electric field-change frequency and the measured electric field, the device provides the user the following three-stage warnings:

[First Warning] --- Thunderstorms have broken out and are active in a distance, and it is possible they will come over the site in about 30 minutes.

[Second Warning] --- Thunderstorms in a distance keep their activity and are approaching closer, and it is possible they will come overhead in 10 minutes.

Fig. 3 Photograph of an in door unit

[Thunderbolt Alarm] --- Thunderclouds are active overhead and it is highly probable that thunderbolts occur nearby.

Fig. 3 shows an indoor unit of the device that has a meter and warning lamps on the front panel. The warnings of three stages are conveyed to the user by lighting of the pilot lamps and sound of the buzzer. The lighting of blue, orange and red lamps shows First Warning, Second Warning and Thunderbolt Alarm, respectively. The movement of the meter pointer also shows the activity of lightning.

5. Issuance of First and Second Warning

The detecting circuit of electric field—changes in Fig. 2 issues the ON signal, when the frequency of detected electric field—changes exceeds the preset value. The preset value is adjusted so that the detecting circuit issues the ON signal when thunderclouds are active within 30 km distance from the warning device site.

The detecting circuit of the electric field issues the ON signal, when the electric field reaches the plus or minus preset value. The preset value is adjusted so that the detecting circuit issues the ON signal when the thunderclouds or strongly electrified clouds approach within 10 km distance.

The outputs of the two detection circuits are combined with "OR" and "AND" combination circuits. "First Warning" is issued by the "OR" combination of the ON signals from the two detecting circuits and "Second Warning" is issued by the "AND" combination of the ON signals from the two detecting circuits.

6. Issuance of Thunderbolts Alarm

6-1. Surface electric field due to thunderclouds and electric field—changes caused by thunderbolts

A thundercloud cell takes the dipole electrical structure during its active period, the positive charge being widely distributed in the upper portion of the cloud and the negative charge being densely distributed in a strong precipitation region, as shown in Fig. 4. Under the dense cloud negative charge, a positive space charge layer is formed near the ground surface (Markson and

Fig. 4 Thundercloud model of dipole electrical structure

Fig. 5 Thundercloud model of tripole electrical structure

Fig. 6 Surface electric field recorded at 5 to 6 km distance from cloud charge center

Anderson, 1988).

In the most active period, a thundercloud cell takes the tripole electrical structure as shown in Fig. 5, and produces W-shape electric field on the ground surface (Chalmers, 1967, p.314). Fig. 6 shows the typical surface electric field recorded at the horizontal distance of 5 to 6 km from the cloud charge center. Since the electric field caused by the cloud negative charge predominates at this distance, the electric field is negative and its amplitude is much larger than the amplitudes of individual field-changes caused by lightning discharges (both intracloud and cloud-to-ground discharges). When the cloud charge center comes overhead, the effect of cloud negative charge is neutralized by the lower positive charge and the surface electric field becomes relatively small compared to the amplitude of field-changes caused by lightning discharges. Fig. 7 shows examples of the electric field-changes, recorded when the charge center comes right above the recording site. In this situation, the amplitude of field-changes caused by close thunderbolts becomes very large and the trace of the field record usually crosses the zero-line. The thunderbolt lowers the cloud negative charge together with the lower positive charge (Clarence and Malan, 1957; Jacobson and Krider, 1976). Usually the amount of the negative charge exceeds that of the lower positive charge and associated field-change exhibits a positive displacement (see Fig. 7a). In case the amount of the positive charge exceeds that of the negative charge, the field-change exhibits

Fig. 7 Sudden electric field-changes across zero line (field-changes close to struck point)

Fig. 8 Map carrying the warning device site X and 5 meteorological institutions ◎

negative displacement (see Fig. 7b, This is a kind of positive ground flashes, but of different nature from one observed in winter thunderclouds). Anyhow, the field-changes across the zero-line are recorded only when the charge center is right above the recording site.

6-2. Issuance of Thunderbolt Alarm

The new warning device includes a Thunderbolt Alarm issuing circuit that is connected to the electric field detection circuit and to the micro-ammeter circuit as shown in Fig. 2. The micro-ammeter circuit contains two relays, the functions of which are adjusted by the two movable pointers on the panel of the meter, one on the positive and the other on the negative zone of the meter panel. The values corresponding to the electric fields immediately

Table 1 Lightning activity records obtained at meteorological institutions surrounding the warning device site

Month	Date	Kumamoto District Observatory (17 km)	Kumamoto Airport Station (6.3 km)	Mt. Aso Station (20 km)	Hitoyoshi Station (73 km)	Ushibuka Station (110 km)	Lightning Activity		
							Distance	Area	Duration
MAR.	24 28	K ¹	K	T ⁰	K K	K K	close	large	1 h
							far	large	
APR.	22			K			medium	small	
MAY	7	K ¹	K	K	K	K	close	large	5 h
JUN.	15	K ¹	K	K	K	K	close	large	1 h 10 m
	16	K ¹				K	medium	large	30 m
	28	K ¹	K		K	K	close	large	1 h
	29	K	K		K	K	close	large	1 h
	30	T ¹			K	K	far	large	
JUL.	2	K ¹	K	K			close	medium	30 m
	10	T ¹		T ¹	K		medium	large	1 h 30 m
	16	T ¹	K	K			close	medium	
	21			T ¹			medium	small	30 m
	23	K	K	T ¹	K		medium	large	10 m
	27	K ¹	K		K		close	small	1 h
	30	T ¹					medium	large	10 m
AUG.	3	K ¹	K	<		<	close	large	12 m
	4	K ¹	K	K			close	medium	40 m
	8	K ¹	K	T ⁰ <	K	<	close	large	1 h
	9	K ¹	K	K	T ¹		close	large	1 h
	10	< ⁰					medium	small	1 h
	12	K ¹	K	T ⁰ <	K	<	close	large	1 h
	13		<	K	K		medium	large	
	15	< ⁰		K	K		medium	large	1 h
	16	< ⁰		<			medium	small	1 h
	17	K ¹	K	T ⁰	K	K	close	large	1 h 30 m
	18	< ⁰	<			<	medium	large	30 m
	22			K	K	<	far	large	
	23	K ¹	K		K		close	large	50 m
SEPT.	1	T ¹	K	K		K	close	small	20 m
	2	T ⁰	K	K	T ¹	<	close	large	30 m
	5	K ¹	<			K	close	large	1 h
	6					<	medium	large	
	7			T ⁰		<	far	large	
	8	T ⁰	<	K		<	close	large	
	12	< ⁰			K	<	medium	large	3 h
	14	< ⁰			K	<	far	large	10 m
OCT.	17	K ¹				K	medium	large	30 m
	6	T ¹		T ⁰	T ¹	K	medium	large	20 m

before and after a close thunderbolt can be preset by the two pointers. When a current pointer of the micro-ammeter crosses two relay pointers successively, the circuit issues Thunderbolt Alarm. Watching the meter pointer, the user can observe temporal variations of the static electric field and sudden changes due to lightning discharges.

7. Lightning activity around the device site during the whole year of 1990

At Honda Driving Plaza in Kumamoto Prefecture, the whole lightning warnings and alarms issued by the device were recorded from January 1, 1990 to December 31, 1990. The authors investigated the lightning activity during this period, observed at meteorological institutions surrounding Honda Driving Plaza and compared it with the issued warnings.

Fig. 8 shows the map that carries the positions of Honda Driving Plaza and five meteorological institutions surrounding Plaza, their name being Kumamoto Airport Weather Station, Kumamoto District Meteorological Observatory, Mt. Aso Weather Station, Hitoyoshi Weather Station and Ushibuka Weather Station, in order of the distances from Plaza. The distances from the above institutions to Plaza are 6.3, 17, 20, 73 and 110 km, respectively. At meteorological institutions lightning, thunder and successive occurrences of lightning and thunder are commonly recorded by the symbols $\angle$, T and $\bar{\kappa}$, respectively. The intensity of the phenomena is shown by the numbers 0, 1, and 2 on the upper right position of the symbols. The daily records of these phenomena are published in the monthly reports of the district meteorological observatory. Kumamoto District Meteorological Observatory also publishes the detailed time-sequence records of the above phenomena observed at the observatory.

During the whole 1990 year, the authors picked up all dates when lighting activity was recorded at least at two institutions among the nearest three ones, namely Kumamoto Airport Station, Kumamoto District Observatory and Mt. Aso Station and listed them on Table 1, where all lightning activity records at the three institutions were entered. On the table, the authors added the lightning activity records obtained at Hitoyoshi and Ushibuka Stations.

Table 2 Issuance of Second Warning and the corresponding lightning activity

Issuance of Second Warning				Lightning Activity			
Month	Date	Duration in hour	Number	Distance	Area	Duration	$\angle$ & T
MAR.	24	09 to 13	13	close	large	1 h	strong
	28	16 to 20	4	far	large	-----	-----
JUN.	14 *	22 to 23	11	medium	small	-----	week
	16	04	1	medium	small	30 m	strong
	28	23	2	close	large	1 h	strong
	30	06	1	far	large	-----	-----
JUL.	21	17 to 18	12	medium	small	30 m	week
	23	18	1	medium	small	10 m	-----
	27	17 to 18	4	close	small	1 h	strong
AUG.	4	20 to 22	12	close	medium	40 m	strong
	12	17	1	close	large	1 h	strong
	23	11 to 12	4	close	large	1 h	strong
SEPT.	1	17	13	close	small	20 m	medium
	2	16 to 18	21	close	large	32 m	medium
	8	16 to 17	38	close	large	-----	medium

* is not listed on Table 1, because lightning activity was recorded only at Kumamoto Observatory.

Table 3 Issuance of Thunderbolt Alarm and the corresponding lightning activity

Issuance of Thunderbolt Alarm				Lightning Activity			
Month	Date	Time in hour	Number	Distance	Area	Duration	⋈ & T
MAY	7	10 to 16	23	close	large	5 h	strong
JUN.	15	17 to 18	6	close	large	1 h 10 m	strong
	29	07	2	close	large	1 h	medium
JUL.	2	14	1	close	medium	30 m	strong
	16	15	1	close	medium	10 m	medium
AUG.	17	16 to 7	24	close	large	3 h 20 m	strong
SEPT.	5	18	2	close	large	1 h 10 m	strong

In Table 1 the authors classified the lightning activity in the following three categories:
[Distance of lightning activity from the site of the warning device]

"close": The case where lightning activity was observed at least at two stations among the nearest three stations.

"medium": Lightning activity was observed at either of Kumamoto Observatory or Mt. Aso Station.

"far": Lightning activity was observed at either or both of Hitoyoshi or Ushibuka Stations.

[Area of lightning activity]

"small": Lightning activity was observed at only one station.

"medium": Lightning activity was observed simultaneously at two stations among the nearest three stations.

"large": Lightning activity was observed simultaneously at one of the nearest three stations and at either of Hitoyoshi or Ushibuka Station, at least.

[Intensity of lightning activity]

"strong", "medium" and "weak": They were judged by the intensity records on ⋈, T and K.

8. Comparison of the alarm records with the observed lightning activity

During the whole 1990 year, the number of days on which warnings or alarms were issued amounted to 89. They were issued as follows:

(a) Number of days on which only First Warnings were issued: 67

(b) Number of days on which only First and Second Warnings were issued: 15

(c) Number of days on which Thunderbolt Alarms were issued: 7

Using Table 1 and the detailed records of lightning phenomena at Kumamoto Observatory, the authors investigated the correspondence of the issued warnings and alarms with the observed lightning activity.

8-1. Comparison of the records of First Warnings with the observed lightning activity

It was found that the issuances of the First Warning were associated with the activity of "far" or "medium" distance and associated with all three area categories, "small", "medium" and "large". Only in two cases, the First Warnings were issued associated with the "close" lightning activity and in these cases, the numbers of successive issuance were extraordinary large, namely 99 and 22. In one specific case, the First Warning was not issued, though the lightning activities of "medium" distance and "small" area was observed.

8-2. Comparison of the records of Second Warning with the observed lightning activity

The authors listed up all lightning activity associated with the Second Warning issuance and made Table 2. On the table, it was found that the Second Warnings were issued either of the following two cases:

- ① The lightning activity of "far" in distance and "large" in area existed.
- ② The lightning activity of "medium" and "close" distance existed, regardless of its area categories.

8-3. Comparison of the records of Thunderbolt Alarm with the observed lightning activity

Table 3 lists up all the lightning activity associated with the Thunderbolt Alarm. In all cases, lightning and thunder were observed simultaneously at Kumamoto Airport Station (6.3 km) and Kumamoto Observatory (17 km). Consequently, it was disclosed that when Thunderbolt Alarm was issued, thunderclouds spread over the device site and the probability of thunderbolts near the site was very high. In 5 cases among 7, the Thunderbolt Alarms were issued by thunderstorms of strong activity and large area.

Comparing Tables 2 and 3, it was found that in 6 cases where lightning activity was "close" and "large", Thunderbolt Alarm was not issued. In these cases, the device did not detect the large electric field-changes across zero line shown in Fig. 7 and actually nearby thunderbolts did not occur around the site.

9. Summary

It is generally expressed that the diameter of thundercloud cell is 5 to 10 km. However, in actual thunderclouds, plural cells of different life-cycle stages are combined in one cloud group and the horizontal extension of an electrically active area has a complex shape. Consequently, it is difficult to estimate exactly the distance of the lightning activity from a warning device site. As to the distance, the authors could express it only in a coarse range.

It is ascertained that the issuance of each warning or alarm is associated with lightning activity in the following way:

[First Warning] --- It is issued when lightning activity arises within the distance of 15 to 80 km, being independent on its area categories. The numbers of the issued warnings for one series of thunderstorms depend on the area and duration of the storms. When the lightning activity situates at the distance of 15 km and does not approach closer, Second Warning is not issued.

[Second Warning] --- It is issued either when lightning activity arises or approaches within the distance of 35 km or when lightning activity of a large area exists at the distance from 35 to 80 km. The numbers of the issued warnings for one series of thunderstorm depend on the area and duration of the storms. First Warning is always issued, from 30 minutes to 3 hours before the issuance of the Second Warning.

[Thunderbolt Alarm] --- It is issued when thunderclouds with strong lightning activity, accompanying thunderbolts come within the distance of 15 km or overhead of the site. The frequency of the issuance depends on the frequency of thunderbolts. Second Warning is always issued, from 0 to 1 hour before the issuance of Thunderbolt Alarm.

Each warning or alarm is always associated with corresponding lightning activity, even if its issuance is only once. So, the device does not fail to issue necessary warning or alarm. At the same time, it is important that the device does not issue any warning or alarm, when lightning activity is not in the case that warning or alarm is actually needed. On Table 2, it is noticed that even if the lightning activity is strong and of large area, Thunderbolt Alarm

is not issued unless nearby thunderbolts occur. It turned out that the present warning device issues appropriate warnings according to the situation of surrounding lightning activity and does not issue any unnecessary warnings. However, the nature of lightning activity of winter thunderstorms along the coast of Japan Sea is fairly different from that of thunderstorms treated in the present article. It is desirable to do similar investigation of the performance of the device installed at a facility situated along the coast of Japan Sea.

For the protection of people and facilities, the device urges the user to take the following precautions:

[First Warning] --- It is possible that thunderstorms will come over the site in about 30 minutes.

[Second Warning] --- It is possible that active thunderstorm will come overhead in about 10 minutes.

[Thunderbolt Alarm] --- It is highly probable that thunderbolts occur nearby.

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