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**The Electric Field Changes and UHF Radiations
Caused by the Triggered Lightning in Japan**

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1. Introduction

A rocket-triggered lightning experiment has a merit that it allows the direct measurement of a lightning current which is one of the important parameters for protection against lightning. It also has a merit that tests on a variety of electric and electronic equipment and arresters can be made by using actual lightning currents. Because of such merits rocket-triggered lightning experiments have been carried out actively in and out of Japan with significant results. Lightning parameters that have been given much attention in such experiments include, in addition to lightning current, the velocity of propagation of the lightning return stroke, lightning channel configuration, and corona currents; many parameters are directly related to lightning and are normally measured at a relatively short distance.

On the other hand, the lightning current and the associated electromagnetic field changes are theoretically related with each other by Maxwell's equations. Just like the cases of natural lightning, electromagnetic field changes are considered to be important indirect or remote sensing measurement parameters for rocket-triggered lightning. In addition to it, as exemplified by the success of SAFIR⁽¹⁾ by the ONERA group of France, the UHF radiation is one measurement parameter worthy of attention for the realization of an interferometric system for the localization of lightning discharge position. In other words, the use of UHF radiation will allow us to know the state of propagation of lightning discharge with higher space and temporal resolutions⁽¹⁾. Furthermore it will enable us to quickly know the conditions just before the initiation of a lightning stroke. Thus the combination of observation of electric and magnetic fields that have been practiced extensively over many years and

observation of UHF radiation has a high possibility of providing an effective measure of protecting an electric power system against lightning.

With such views in mind, we conducted rocket-triggered lightning experiments (at Okushishiku Kogen) in fiscal 1989, and measured the electromagnetic field changes and the UHF radiation intensity accompanying triggered lightning, by means of a slow antenna, a fast antenna, a loop antenna, and a disc antenna, at a base camp 2.5 km away from the rocket launching site. This paper presents the results of the observation, and discusses the rocket-triggered lightning from the view points of electromagnetic field changes and the UHF radiation.

2. Observation System

The observation system used in the rocket-triggered lightning experiments of fiscal 1989 will be outlined below, in two parts; the sensor block and the recording block, respectively.

(Sensor Block)

(a) Measurement of electric field changes at the ground level

To grasp the state of lightning discharge, the electric field changes were measured with two disc antennas. A disc antenna was a combination of an electrostatic antenna and an amplifier. The electrostatic antenna was a metal disc of several tens of centimeters in diameter placed horizontally at a level of several tens of centimeters above the ground. One disc antenna was the fast antenna with a time constant of 1 ms and a frequency band ranging from several hundreds Hz to 2 MHz, that was designed to cover rapid changes of electric fields associated with return strokes of lightning. The other disc antenna was the slow antenna with a time constant of 5 s and a frequency band ranging from 0.1 Hz to 1 kHz, that was designed to cover relatively slow changes of electric fields before and after a lightning discharge⁽²⁾.

(b) Measurement of changes of magnetic fields

Magnetic field changes associated with lightning discharges were measured with a single loop antenna. This antenna output was also used as a trigger signal of the recording system (4 ch

digital memory) that will be explained later.

(c) Measurement of UHF radiation

UHF waves (327 MHz) radiated in the early stage of the discharge were measured by means of the disccone antenna. We used the disccone antenna ⁽⁴⁾ because it has the following merits:

- (1) As the antenna has a wide band, it is convenient for selecting, during measurement, a frequency range with less background noises such as radio broadcasting waves;
- (2) As the antenna is nondirectional, it is capable of receiving atmospherics from any direction; and
- (3) It does not give corona discharge even in strong electric fields.

(Recording Block)

The outputs of the fast antenna, slow antenna, and disccone antenna were recorded by a 4-ch digital memory unit (System 1) in which one word comprises 12 bits to have a wide dynamic range. The sampling frequency was 1 MHz, and the total capacity of the temporary storage was 64 kilowords for each channel, and the working record length was 64 milli-seconds. Measurement of electric field changes by means of the long-time waveform recorder described in reference ⁽⁵⁾ was also made simultaneously. Although detailed description is omitted here, the recorder is indicated as System 2 in this report. The configuration of the total system is shown in Fig. 1.

3. Electromagnetic Field Changes and Rocket-triggered Lightning

Rocket-triggered lightning is a method of triggering a lightning by launching a small rocket of about 20 cm in length, to which a steel wire of 0.2 mm in diameter is connected, under thundercloud. When the rocket ascends, an electric field is concentrated at the top end of the rocket, and a leader will initiate towards the thundercloud, and lightning will be triggered along this weakly ionized channel. In a rocket-triggered lightning experiment, two kinds of rocket-triggered lightning tests, rocket-triggered lightning to the ground, and rocket-triggered lightning to the tower, are normally made under different conditions. The rocket-triggered lightning to the ground is a system in which the wire connected to a rocket is extended to the ground. On the other hand, the rocket-triggered

lightning to the tower means that the rocket itself is isolated to the ground. A nylon thread is paid out up to a height of about 100 m above the ground, and then from that point a steel wire is paid out. As the rocket assembly is insulated up to 100 m above the ground, a downward-moving leader can be initiated from the lower end of the wire to a power transmission tower of 60 m high^{(3),(8)}.

The rocket-triggered lightning experiment of fiscal 1989 was conducted by using the test transmission line and a tower on the top of Mount Okushishiku (930 m above the sea) from November 6, 1989 to December 5, 1989. The observational results of the individual rocket-triggered lightning experiments are summarized in Table 1. Marks \circ \times $-$ denote successful collection of data, failure in data collection, and no observation, respectively. Examples of actual observed waveforms are shown below, one each for the lightning to the tower and the lightning to the ground. Ez and B of the diagrams indicate the vertical electric field strength on the ground and the interlinkage magnetic flux density, respectively. Their intensities are relative ones.

Fig. 2 shows waveforms of electromagnetic field changes for the experiment number 89-07 (rocket-triggered lightning to tower). Fig. 2-a shows of electric field change for a portion of 512 micro-seconds which is considered to correspond to the initiation of triggered lightning, out of the whole record length of 64 milli-seconds. Fig. 2-b shows magnetic field change for the same time period. Fig. 2-c shows electric field change triggered by this rocket-triggered lightning experiment for 262 milli-seconds; the data of the entire triggered-lightning experiment were recorded by the long-period waveform recorder. On the other hand, Fig. 3-a, b, c show the electromagnetic field changes of the portion corresponding to the initiation of the triggered lightning and the whole signature of lightning of the experiment number 89-11 (rocket-triggered lightning to ground). Although not shown here because of the limited space, all of the other results of observation were similar to those shown in Fig. 2 and Fig. 3. In the electromagnetic field changes of rocket-triggered lightning, we found no rapid changes corresponding to return stroke of natural lightning. Moreover, the relatively slow changes, as shown in the traces, were superimposed with impulse-like waveforms. The phenomenon of superimposing with many impulses was similar to the result obtained by Yoda et al.⁽⁷⁾ for the direct measurement of lightning stroke current.

Next, we will compare the waveforms of the electromagnetic

fields obtained in the rocket-triggered lightning to tower and those of the rocket-triggered lightning to ground to identify discrepancy between the two methods. In the case of rocket-triggered lightning to the tower, as shown in Fig. 2-a and b, a bipolar pulse of a relatively large amplitude is present in the portion corresponding to the initiation of triggered lightning. In contrast, as shown in Fig. 3-a and b, in the case of the rocket-triggered lightning to ground, there is no bipolar pulse with a relatively large amplitude at the initiation of triggered lightning, and the amplitude of the impulses tends to get larger gradually. Such differences of waveforms of electromagnetic fields between the two triggered-lightning methods were not confined to the particular cases shown above, but common to all of the results of observation during this experiment.

From the results of observation of the past rocket-triggered lightning experiments, it is known that, in the case of rocket-triggered lightning to tower, as the rocket and the wire connected to it are insulated from the ground, leaders of different polarities propagate upward from the lightning inducing point of the rocket and downward from the lower end of the wire, respectively, to eventually trigger a lightning, whereas, in the case of rocket-triggered lightning to ground, as the rocket is grounded by the wire, the leader propagates only upward from the lightning inducing point of the rocket.⁽⁸⁾ The differences of the waveforms of electromagnetic fields at the initiation of triggered lightning between the triggered-lightning to tower and the triggered-lightning to ground and the presence of bipolar impulse of a large amplitude of the present results were attributed to the differences between the lightning triggering mechanisms of both the methods as described above. We are now examining the causes in detail.

4. Preceding UHF Pulses

In this section we will discuss the relationship between electromagnetic field changes during a rocket-triggered lightning and accompanying UHF electromagnetic radiation.

Fig. 4 shows magnetic field changes before and after the initiation of the triggered lightning of the experiment number 89-04 (triggered lightning to the tower) and the accompanying UHF electromagnetic radiation. As discussed in the preceding section, the magnetic field waveform has a bipolar pulse, which is a feature of the rocket-triggered lightning to the tower, at the initiation of the triggered lightning. On the other hand, as

clearly shown by the diagram, the UHF electromagnetic radiation preceded the bipolar pulse of the changes of magnetic field corresponding to the initiation of the discharge. Pulses were isolated each other before the bipolar pulse, but after the bipolar pulse the radiation intensity increased suddenly and the state of radiation was like a burst. Such a sudden change of the UHF radiation intensity was similar to the states of UHF radiation before and after a return stroke of natural lightning shown in Fig. 5.

The burst-like change of UHF radiation of natural lightning is attributed to the net-shaped propagation of the return stroke in the cloud after it reaches the bottom of the cloud.⁽⁹⁾ If the change of UHF radiation observed in rocket-triggered lightning were generated by the same cause with natural lightning, the isolated UHF pulses of Fig. 4 could be attributed to leaders moving upward from the rocket or leaders moving downward from the lower end of the wire. The mean time intervals of the isolated pulses of Fig. 4 is about 27 micro-seconds which is close to the statistical values ranging from 29 to 52 micro-seconds for time intervals of stepped leaders.⁽¹⁶⁾

The distributions of time intervals of isolated UHF pulses observed in the experiment numbers 89-04 and 89-7 (triggered lightning to the tower) are shown in Fig. 6. The transitions of time intervals of these pulses are shown in Fig. 7. The pulse number of Fig. 7 indicates the numbers given to the isolated pulses initiation from the first pulse. Thus Fig. 7 shows that the time interval between two consecutive pulses get shorter with the passage of time. This feature is similar to that observed in stepped leaders of natural lightning.⁽¹¹⁾

We have described the magnetic field changes and UHF radiation of the rocket-triggered lightning to tower. Similar phenomena were observed in the rocket-triggered lightning to the ground although there were some differences. Fig. 8 shows the changes of magnetic field and UHF electromagnetic radiation of the experiment number 89-11 (rocket-triggered lightning to the ground). The UHF radiation showed isolated pulses preceding the first magnetic field change. The changes from isolated pulses to burst-like pulses, however, were not so rapid as those observed in the rocket-triggered lightning to the tower.

Some statistics of the UHF isolated pulses preceding the magnetic field changes observed during the rocket-triggered lightning to the tower and to the ground are shown in Table 2; the number of pulses, pulse intervals, and the time duration up to the changes of magnetic field. In the table the polarity

indicates the polarity of the lightning stroke current measured at the launching point of the rocket.⁽¹²⁾ For those to which this datum is not available, the polarity of the point corona current at the time of launching of the rocket is shown in parentheses.⁽¹³⁾ When the number of pulses and the polarity of induced lightning were examined for the rocket-triggered lightning to tower according to the statistics, the positive rocket-triggered lightning tended to have smaller number of pulses than those of negative polarity. On the other hand, in cases of the rocket-triggered lightning to the ground, the relationship between the number of pulses and the polarity was not as clear as that of the rocket-triggered lightning to tower. When we examined the number of pulses and the time duration from rocket launching to triggering⁽¹³⁾, the lightning, both to the tower and to the ground, having longer time duration up to triggering tended to have a greater number of pulses.

5. Concluding Remarks

In the rocket-triggered lightning experiment of fiscal 1989, we observed electromagnetic field changes and UHF electromagnetic radiation accompanying rocket-triggered lightning. The findings were as follows:

- (1) No rapid changes corresponding to the return stroke of natural lightning were observed in the electric field changes accompanying rocket-triggered lightning. Continuous currents, however, were present.
- (2) In the case of the rocket-triggered lightning to the tower, in electromagnetic field changes corresponding to the initiation of triggered lightning showed a bipolar pulse of a relatively large amplitude. In contrast, the rocket triggered lightning to the ground did not have such a bipolar pulse.
- (3) The UHF radiation accompanying the rocket-triggered lightning preceded the waveform portions corresponding to the first changes in electromagnetic fields. In particular, in the case of the rocket-triggered lightning to the tower, the UHF radiation showed a change from isolated pulses to burst-like pulses of larger amplitude across a bipolar pulse of a relatively large amplitude in magnetic field.
- (4) The number of isolated pulses in the UHF radiation showed a

correlation with the time duration from rocket launching up to triggered lightning. The time interval between consecutive isolated pulses tended to get shorter with the passage of time just like the stepped leaders of natural lightning.

Physical interpretation of the above-mentioned features of the rocket-triggered lightning of the present experiment is a future task, and is expected to contribute much to the understanding of winter lightning of Japan.

To be more specific, the feature of (1) above differs from that of the electric field changes observed in the rocket-triggered lightning experiment at the U.S. Kennedy Space Center indicated in reference ⁽¹⁴⁾ in that the changes in electric field of the latter showed a rapid change corresponding to return stroke. The difference is attributed to that our experiment was conducted in a mountainous area while the U.S. experiment was conducted in a place of the sea level. In other words, their experimental condition was close to an ordinary lightning stroke with the bottom of the cloud being fairly high above the ground, whereas our experiment was made in the thundercloud, and the triggering conditions were similar to those of intracloud discharge. It should be noted that the transmission towers erected in the mountainous areas of Hokuriku District tend to be covered by thunderclouds in winter. As their environment is comparative to that of our experiment, the result of our experiment discussed in Section 3 or relatively slow changes overlapped by many pulses is attributed to propagation of negative leaders from the top of the rocket to the interior of the cloud. This, in turn, is expected to be of some help in understanding the mechanism of the "triggered lightning" that is started by an upward-moving leader from a transmission tower.

One possible cause of (2) may reflection of current. It, however, is difficult to make a conclusion on the basis of the present experiment alone. Nevertheless, as clearly shown in reference ⁽¹⁵⁾, the results of our measurement and the results of the direct measurement of current conducted by the Chubu Electric Power Co., Inc. agree well with each other. This agreement suggests our method of observation can be applied to lightning strokes to transmission towers to which the direct measurement is not applicable.

With regard to (3) and (4), it is indicated in reference ⁽¹⁾ as well as in reference ⁽¹⁶⁾ that VHF radiation waves are used in the interferometric system to understand the discharge inception mechanism; nevertheless, such research efforts are not present at

all in Japan. We will try to utilize our results in development of techniques for measuring inside thunderclouds by means of UHF or VHF.

To the best of our knowledge, the significant difference between the discharge inception portion of the rocket-triggered lightning to the ground and that of the rocket-triggered lightning to the tower have not been reported up to now. This may provide, if we repeat experiments and continue theoretical investigation, a clue to the discovery of the "discharge inception mechanism." Furthermore, the UHF isolated pulses preceding to the discharge inception portion suggest a possibility of prediction of lightning stroke although the time allowance is very short. It will mark a step forward towards the ultimate objective of elimination of lightning.

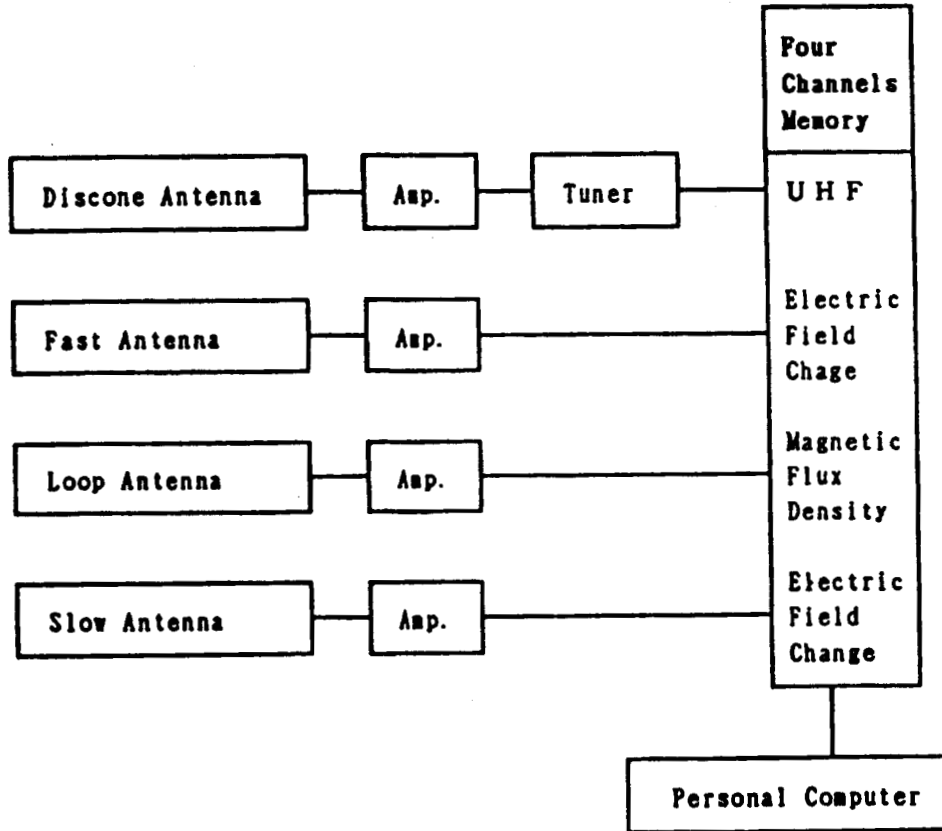
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SYSTEM I



SYSTEM II

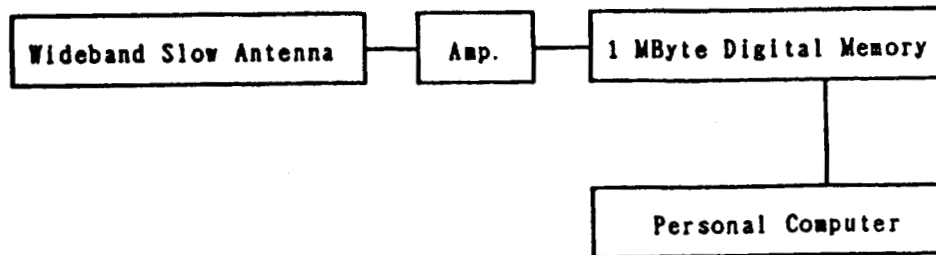


Fig. 1 A schematic of the observation system

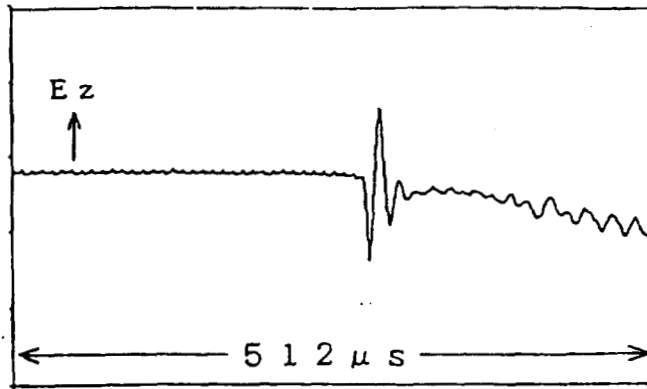


Fig. 2-a The initiation of an electric field change caused by the rocket triggered lightning to the power transmission tower

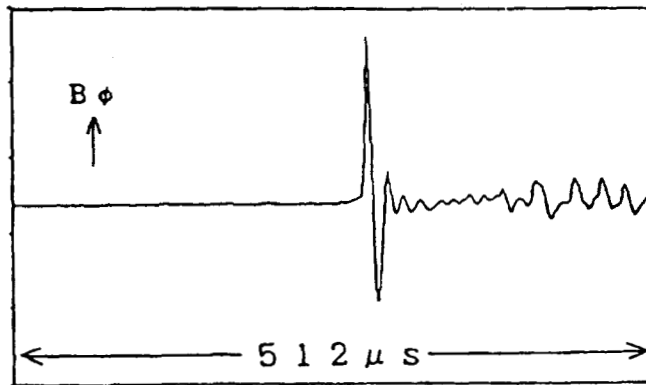


Fig. 2-b The initiation of a magnetic field change caused by the rocket triggered lightning to the power transmission tower

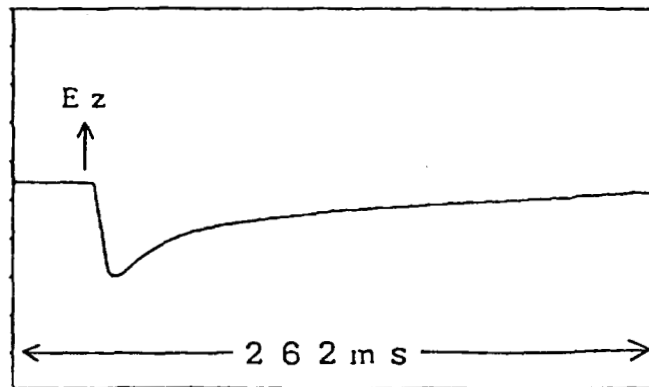


Fig. 2-c The whole signature of an electric field change caused by the rocket triggered lightning to the power transmission tower

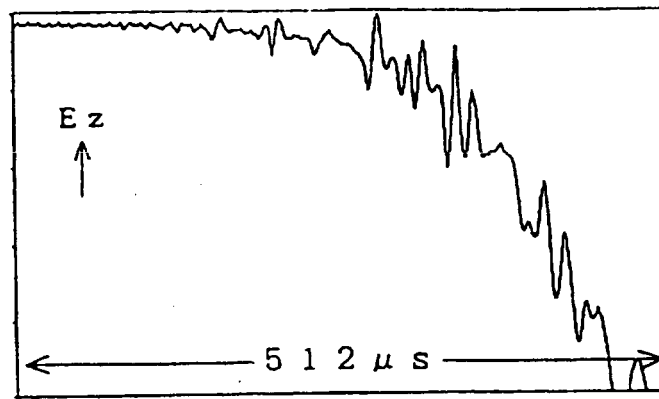


Fig. 3-a The initiation of an electric field change caused by the rocket triggered lightning to the ground

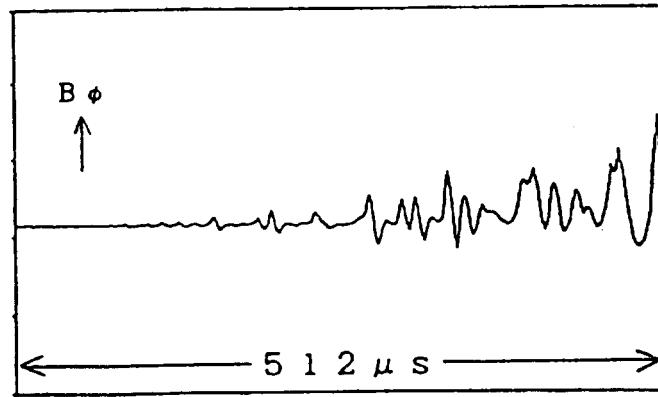


Fig. 3-b The initiation of a magnetic field change caused by the rocket triggered lightning to the ground

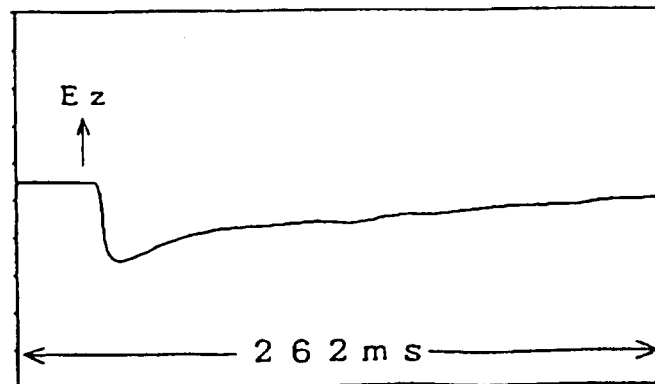


Fig 3-c The whole signature of an electric field change caused by the rocket triggered lightning to the ground

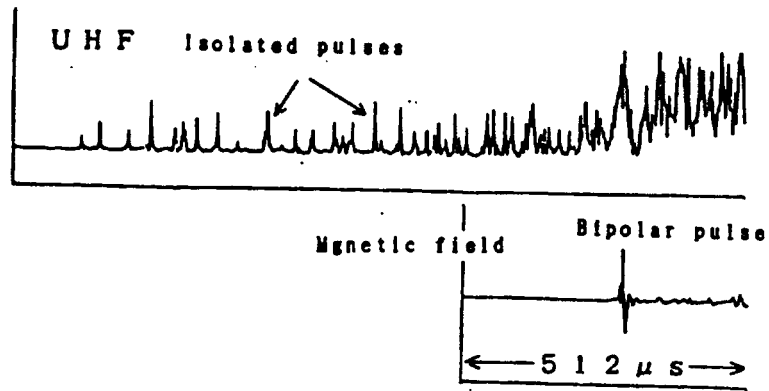


Fig. 4 The preceding UHF isolated pulses of the rocket triggered lightning to the power transmission tower

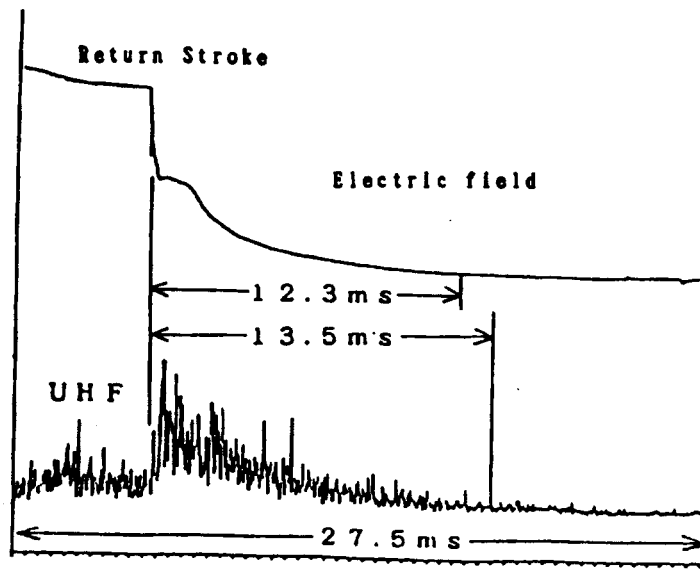


Fig. 5 The electric field change and UHF radiations by a natural positive cloud to ground strike

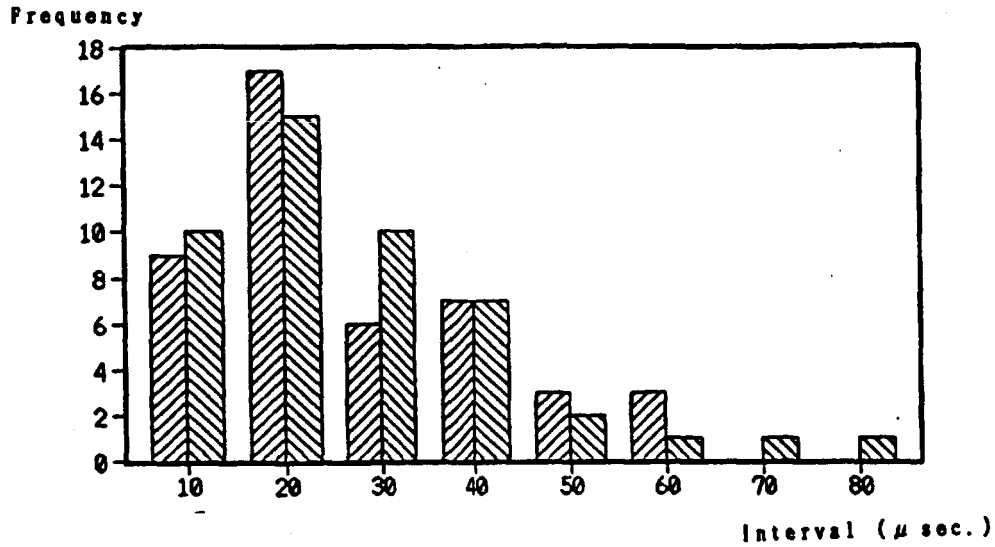


Fig. 6 The statistics of time intervals for UHF isolated pulses preceding the triggered lightning to the power transmission tower

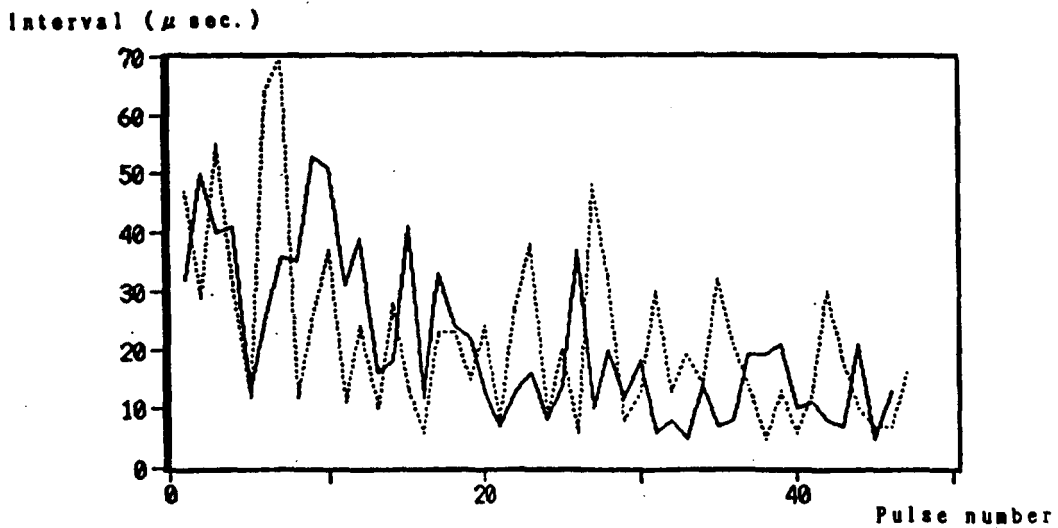


Fig. 7 The transitions of time intervals for UHF isolated pulses preceding the triggered lightning to the power transmission tower

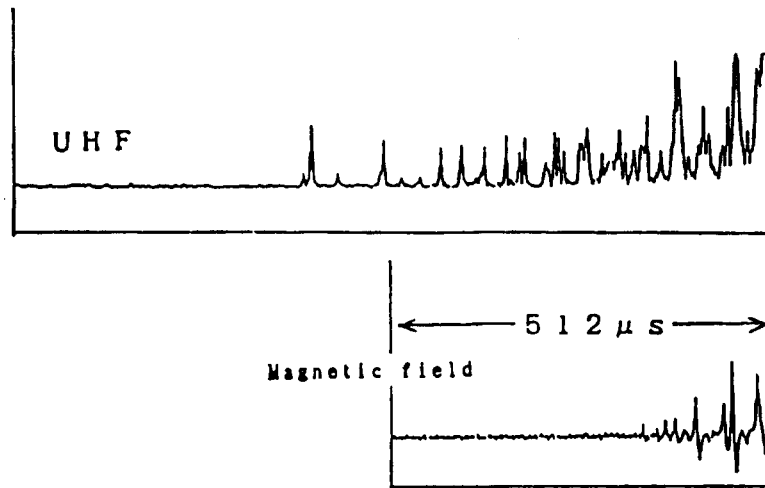


Fig. 8 The preceding UHF isolated pulses of the rocket triggered lightning to the ground

Table 1 The results of the measurement during the rocket triggered lightning experiment

Rocket No.	SYSTEM I				SYSTEM II	
	URF	FAST	SLOW	LOOP	WIDEBAND	SLOW
89-04	○	○	○	○	○	
89-05	○	○	○	○	○	
89-06	○	○	○	○	○	
89-07	○	○	○	○	○	
89-08	○	○	○	○	○	
89-09	○	○	○	○		×
89-10	○	○	○	○	○	
89-11	○	○	○	○	○	
89-12	○	-	-	○		×
89-13	-	-	-	-		-
89-14	○	-	-	○	○	
89-15	-	-	-	-		-
89-16	○	-	-	○	○	
89-17	○	-	-	○	○	
89-18	○	-	-	○	○	
89-19	×	×	×	×		×
89-20	×	×	×	×		×
89-21	×	×	×	×	○	
89-22	○	-	-	○	○	

○ denotes data can be recorded.
 × denotes no data can be recorded.
 - denotes no measurement.

Table 2 The statistics of the UHF isolated pulses
of the rocket triggered lightning

	Rocket No.	Frequency of pulses	Pulse intervals AV. & SD. (μ sec.)		Durations (μ sec.)	Pola- rity
Tower	89-04	46	21.2	13.8	951	-
	89-05	63	26.7	39.8	1695	
	89-07	47	22.1	15.2	1036	
	89-09	8	28.1	10.0	221	
	89-10	10	29.2	34.5	197	
	89-16	34	31.6	20.8	1075	-
Ground	89-06	13	41.5	61.8	557	-
	89-11	17	22.1	13.3	385	-
	89-14	2	312		312	
	89-18	0				+
	89-22	1			53	-