ESTIMATION OF CHARGE DURING A LIGHTNING FLASH USING ELECTRIC FIELD MEASUREMENTS

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1   INTRODUCTION

Electric power utilities have sustained significant damage from lightning. The occurrence of line faults is one result of lightning damage. To prevent it, power utilities adopt various measures of protection from lightning. Transmission line overhead ground wires greatly contribute to a decrease in the number of line faults by preventing direct hits to the power lines.

Lightning that contains a large amount of current raises the potential of the tower although the ground wire prevents direct hits to the power line. As a result, back-flashover may be generated on transmission line insulators, and power failure can occur. It is possible to specify the fault point by using the observed data along with a Lightning Location System (LLS), as back flashovers tend to be generated by the large current lightning events.

However, LLS data is not effective in locating damaged equipment parts. For instance, the ground wire sometimes sustains damage when a strand breaks as a result of its role of preventing direct hits to the power line. Figure 1 is a photograph of a ground wire that was damaged by lightning, Shimizu et al. (2006). To ensure reliability, public security and a consistent power supply, the electric power utilities should strive to locate damaged wires immediately, and take appropriate action.

From previous research, Sunabe and Mitani (1983), Yokoya et al. (1994), and Goda et al. (2006), it is clear that the probability of damage to the shield wire is greatly dependent on the amount of charge contained in a lightning flash. It is difficult to locate the damaged part of the shield wire using LLS data, as the LLS cannot provide an accurate of the amount of charge in a lightning flash. Therefore, substantial labor and financial resources are required for maintenance workers to locate the damaged part of the ground wire on transmission lines.

In view of this background, we studied the estimation of lightning charge using electric field (E-field) measurements in Suzuki et al. (2006). In this thesis, we will introduce the outline of our E-field observations campaign and the results. Moreover, we will describe the effect of digital wave processing technology and the method of extracting data from E-field waveforms for charge estimation.

Figure 1. Photograph of ground wire (80sq. OPGW/AC) that was damaged by lightning.

2 ELECTRIC FIELD WAVEFORM OBSERVATION SYSTEM

The location of the E-field wave measurement systems are shown in Figure 2. The Chubu Electric Power Co., Inc. (CEPCO) LLS is composed of eight IMPACT sensors, installed at intervals of about 100km. The E-field observation equipment is set up at two sites, Nakatsugawa and Ogaki, where LLS sensors are also installed, and we have been taking measurements since 2004. These observation sites are located in one of the areas where lightning occurs most frequently in Japan. Moreover, many transmission line trunk lines pass through this area, and the need for efficient inspection by maintenance workers is high.

Generally, the mono-pole model is used for estimating the amount of electric charge in a lightning flash, taken from multi point E-field data, Krehbiel et al. (1979). Figure 3 shows the principle behind estimating the amount of electric charge in lightning. The relationship between the amount of E-field change (dE) and the amount of charge in lightning (Q) is expressed in Equation (1).

$$dE = -\frac{1}{4\pi\varepsilon} \cdot \frac{2Qz}{\left[(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2\right]^{3/2}} \quad (1)$$

Since there are four unknown parameters (dE, x, y, and z) in this equation, four or more measurement data are required to estimate the amount of the charge (Q) when only E-field observation data is used. In this observation, we estimated the amount of charge (Q) and the height of the electric charge (z) using E-field change data from two sites and the striking point data (x, y) from the CEPCO LLS. That is, the lightning is assumed to be a vertical discharge to the ground.

The E-field measurement system specifications are shown in Table 1. We use an electrode disk whose diameter is 250mm for the E-field antenna. The frequency band of this slow antenna is 0.01Hz-10kHz. In addition, we employed the antenna module and the measurement circuit of the LLS sensor as the fast antenna for measuring E-field change in high frequency bands. The frequency band of this fast antenna is 1kHz-350kHz. To observe all aspects of the lightning discharge, these measuring systems record the E-field change for about one second.

Figure 4 is a flow chart for estimating the amount of charge. In this observation, two methods – analogue measurement and measurement using digital processing – are used for the purpose of comparing the results. Although these two observation techniques are different in their analytical procedure, they both use E-field differentiation waveforms (dE/dt) to detect the E-field change, and subsequently to read the amount of change from the E-field waveform (E). The main activities of FS (Field-monitoring Station) are waveform observation and the extraction of data necessary for estimating the charge amount. Sensor output data after A/D conversion is always recorded in the memory for pre-triggered parts. At the time of detecting the electromagnetic radiation caused by lightning, the sensor output data is recorded for about one second, including the pre-triggered part. Thereafter, the data set that consists of the amount of E-field change and the time (begin/end) are made from the E-field waveform (E) and E-field differentiation waveform (dE/dt). We were able to complete this analysis in real-time with a PC set up at the FS.

The amount of charge is estimated at the CA (Central Analyzer) using the E-field change data sent from the FS. After collating the E-field change data with the LLS data at the CA, the amount of charge is calculated. As mentioned above, two or more E-field change data are necessary to estimate the amount of charge. When data is obtained at only one site, the amount of charge is estimated by assuming the charge altitude. The presumed charge altitude is based on upper-level weather data. Figure 5 shows the monthly average height of the -10 degrees centigrade level from upper-level weather data measured at Wajima for 30 years. It is known that the -10 degrees centigrade level forms the boundary between positive charge, composing the upper part, and negative charge, the lower part, in thunderclouds, Takahashi (1978). Therefore, we use the value indicated in Figure 5 as the charge altitude for estimating the charge amount. In cases where the altitude calculated by two participating sensor is not reasonable, the presumed charge altitude is used.
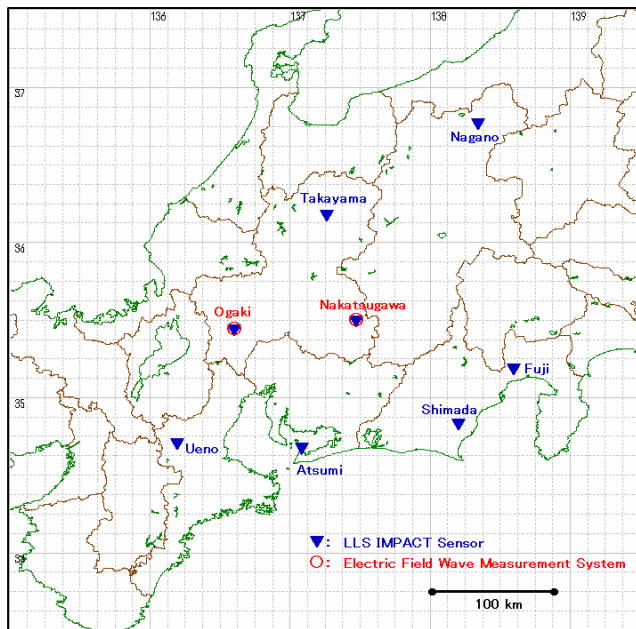
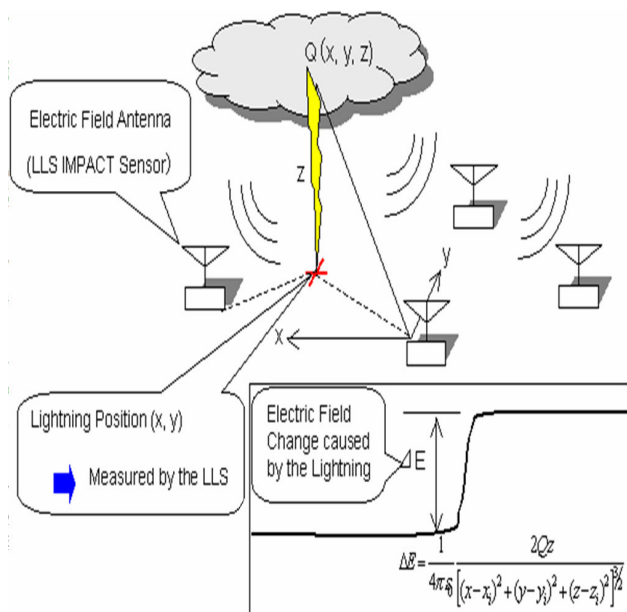Figure.2. Location of the LLS sensors and E-field Wave Measurement Systems.

Figure 3. Principle behind estimating the amount of electric charge in lightning.

Table 1. E-field Measurement System Specifications.

| Equipment	Item		Specification
Low frequency electric field measurement equipment (Slow antenna)	Electric field sensor	Antenna	Electrode disk 250mm in diameter
	Integration amplifier	Amplifier	External and internal amplifier
		Frequency band	0.01 Hz - 10 kHz
	Waveform recording equipment	Sampling	100 kHz
		Memory	128 kword
		Recording duration	1.28 second
		Resolution	12 bit
High frequency electric field measurement equipment (Fast antenna)	Electric field sensor	Antenna	Electrode disk 250mm in diameter
	Integration amplifier	Amplifier	Internal amplifier (LLS sensor)
		Frequency band	1 kHz – 350 kHz
	Waveform recording equipment	Sampling	2 MHz
		Memory	2 Mword
		Recording duration	1 second
		Resolution	12 bit
GPS clock	Time accuracy		±0.5 µsec
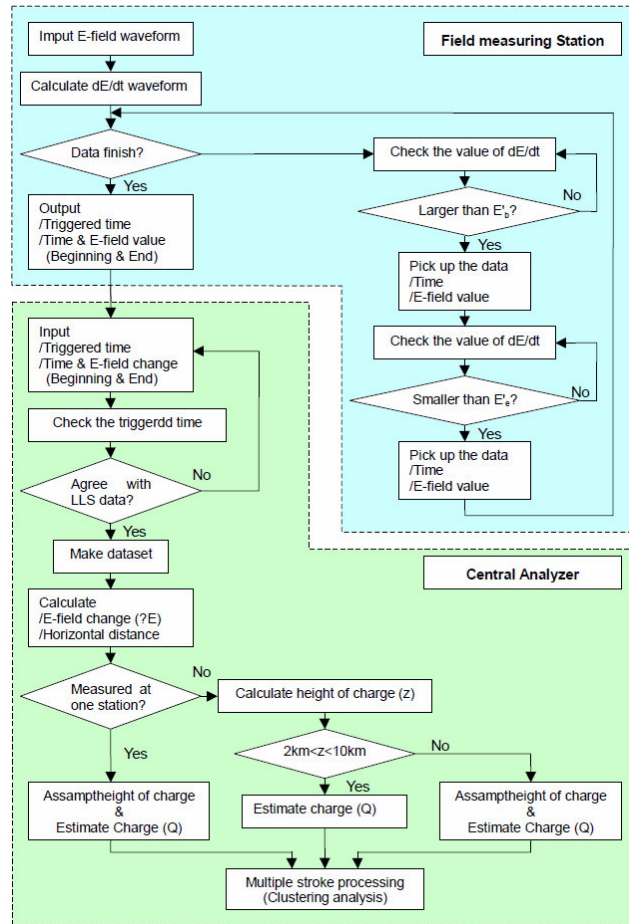
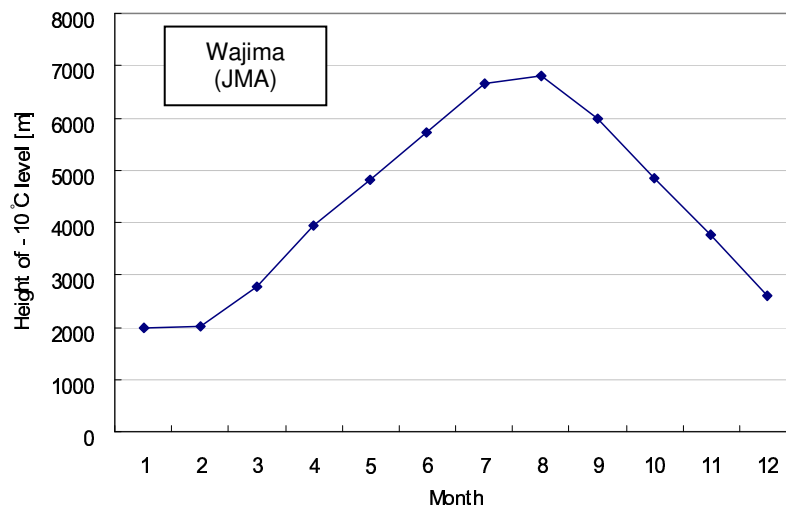Figure 4. Flow chart for estimating the amount of charge.

Figure 5. Monthly average height of -10 degrees centigrade level estimated from upper-level weather data measured at Wajima for 30 years.

3 INVESTIGATION OF WAVE PROCESSING METHODS

3-1 Application of digital wave processing

The electric field signal attenuates greatly relative to its distance from the lightning strike location. Therefore, the following improvements are necessary to detect the lightning E-field change from a great distance:

(1) Reduce background noise

(2) Produce a sensor with high sensitivity and expand the dynamic-range of the measurement system.

The E-field antenna works as a differentiation circuit below the cutoff frequency. Therefore, the E-field waveform is obtained by integrating the output signal of the sensor and amplifying it. However, there is a problem with this method. The amplification rate of the integration amplifier decreases as the cutoff frequency is lowered. Because it is extremely difficult to improve the measurements by improving the hardware, a technique using digital signal processing is being investigated to reduce the background noise.

The digital integration method that we have been investigating is to integrate the output signal of the E-field sensor, converted by an A/D converter, using digital calculation. The features of this method are as follows:

(1) The time constant of the integrator is infinity in theory, and it operates as an ideal integrator.

(2) There is no decrease in the amplification rate due to lowering the cutoff frequency. As a result, high sensitivity measurements can be attempted.

Therefore, it becomes possible to pick up even minute E-field changes buried in the background noise of the integration amplifier. An example comparing the analog integration amplifier E-field waveform output and the digital integration output is shown in Figure 6. In the waveforms output by the integration amplifier, the E-field change caused by the lightning discharge can be distinguished from the noise. We can also the E-field change in steps caused by return strokes clearly depicted in the waveforms recorded using digital integration. However, the digital integration processing technique is flawed. It is greatly influenced by the offset of recording systems, such as the A/D converter. To measure the E-field change accurately, it is necessary to remove the influence of these offsets.

By applying a digital integration process, electro-magnetic noise can be lowered. However, the superimposed commercial power line (60Hz) noise becomes remarkable, as shown in Figure 6. The noise is not overwhelming, but it is undesirable when attempting to detect the E-field change caused by lightning at great distance. For that reason, we have located the observation sites as far from distribution lines as possible. However, it is difficult to remove the commercial power frequency noise completely, because the measuring equipment requires a power supply. Therefore, in the future we are going to investigate the possibility of digitally filtering the commercial power frequency noise during the data analysis process.
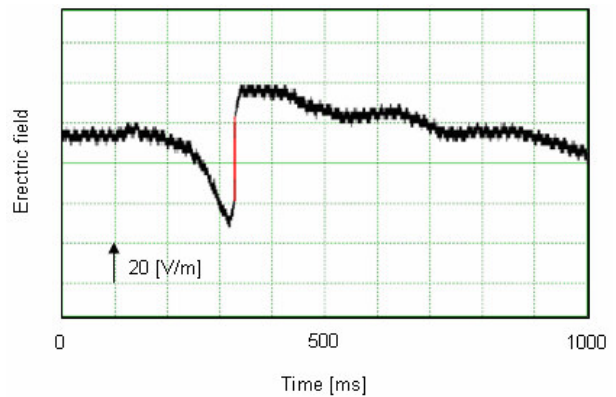
(a) Analog Integration Amplifier Output
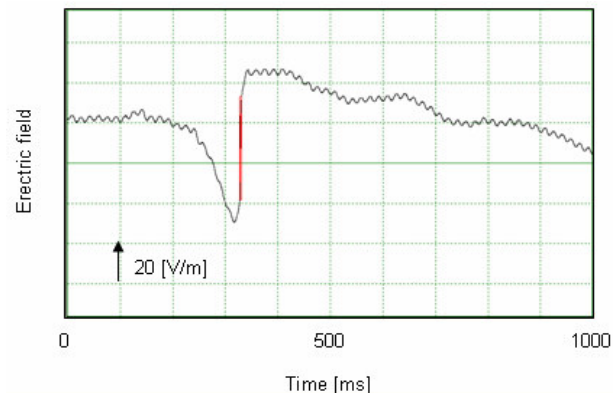
(b) Digital Integration Output
Figure 6. Example of Comparing the E-field Waveforms.

3-2 Processing to extract the change in electric fields

It is not efficient to do this analysis at the CA after it receives waveform data from the FS, because of limits in the capacity of the communication route and the short intervals between lightning flash occurrences. Therefore, we have constructed a procedure to estimate the charge in the lightning flash as shown below. First, only the data necessary for the estimation of charge in lightning flashes is extracted from the E-field change waveform, and transmitted by the FS. The definitions of the parameters that relate to data extraction are shown in Figure 7. The following parameters are extracted from the E-field waveform as necessary data for estimating the amount of the charge, and these are recorded with the waveform triggered-time data.

- Amount of the E-field change (ΔE)
- Beginning time of the E-field change (t_b)
- Ending time of the E-field change (t_e)

At first, we set a constant value threshold for the E-field differentiation waveform (dE/dt) to detect these parameters approximately, and to test the method of extracting the beginning point and the end point of the E-field change. However, this method did not progress smoothly. It is easy to detect the change caused by a return strike using this method, because it is a dramatic change. But it is difficult to specify the end point. The method was improved as follows:

- The threshold level of the beginning point was set to enhance the identification of noise.
- The threshold was set low to make the identification of the end point with noise comparatively easy.

The amplitude of the dE/dt waveform, E'_{max}-E'_{min} are read, and the threshold value of the beginning point, E'_b, and that of the end point, E'_e, are set as shown in Equations (2) and (3). The ratio of the threshold level of the beginning point to the end point is set at 50:1.

$$E'_b = 0.2 \cdot \left(E'_{max} - E'_{min} \right) \qquad (2)$$

$$E'_b = \frac{1}{50} \cdot E_e \qquad (3)$$
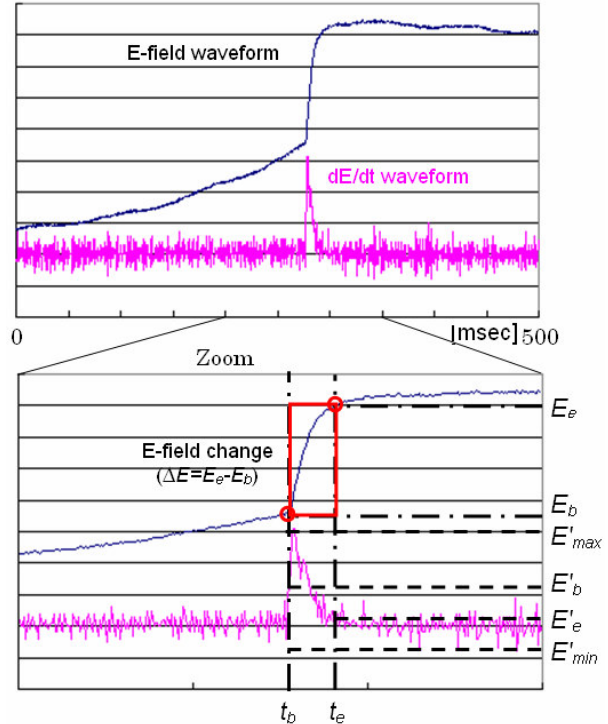
E'b: Threshold level (beginning)
E'e: Threshold level (end)
Figure 7. Definitions of parameters that relate to data extraction.

4   RESULTS OF OBSERVATION

In this paper, we mainly describe the results of analyzing data observed in August 2006, although, in total. we have observed E-field waveforms for about four years. Until now, there was a limit in the performance of the waveform analysis (number of data). Because it has become possible to extract the amount of E-field change automatically using a PC, a lot more data can now be analyzed. Also, analytical accuracy can be expected to improve thanks to the statistical analysis of a great volume of data related to the charge in lightning.

Our analysis of the amount of charge used 13,012 pieces of data that had been obtained at the Ogaki FS and 14,166 items obtained at the Nakatsugawa FS during August 2006. From that data set, we analyzed 6,331 charge estimates from the E-field waveforms obtained at the Nakatsugawa FS. Therefore, the following data describes the characteristics of the charge in typical summer lightning.

The relationship between the amount of charge and the measured E-field change is shown in Figure 8, along with the relationship between them based on Equation (1) at distances of 10km, 20km, 50km, and 100km. This shows that the amount of charges exceeding 12C can be calculated at a distance of 100km by measuring E-field changes of 1 V/m or more. This means that lightning strikes containing charges greater than 12C in the supply area of CEPCO can be identified using electric field measurements made by the sensors in the CEPCO LLS currently installed at intervals of about 100km.

The accumulative frequency distribution of the amount of charge is shown in Figure 9. These data detail the charge contained in lightning strokes. Figure 9 indicates that the 50% value of the amount of the charge slightly exceeds 1C, in both positive and negative flashes. We could see that about 12% of negative lightning strokes and about 53% of positive lightning strokes exceed 10C. These results correspond closely with previous observation records, such as Suzuki et al. (2006).
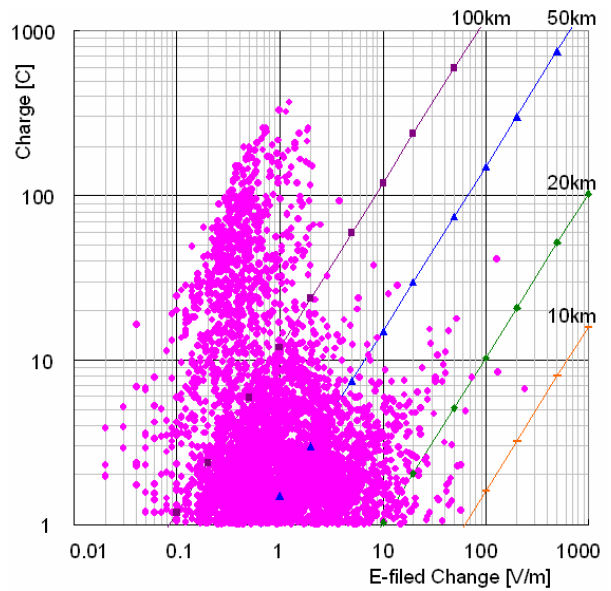

Figure 8. Relation between the E-field changes measured at Nakatsugawa and the calculated amount of charges.
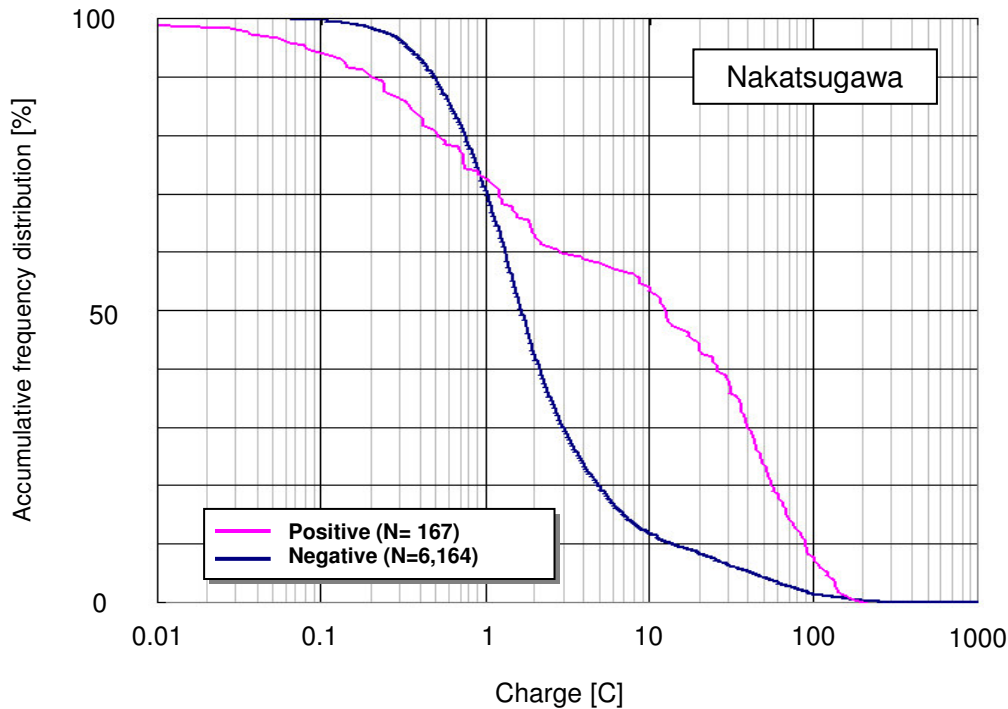

Figure 9. Accumulated frequency distribution of charge in lightning strokes measured at the Nakatsugawa FS in 2006/08. (Positive strokes N=167, Negative strokes N=6,164).

5 CONCLUSIONS

Lightning that contains a large amount of electric charge can sometimes cause serious damage to electric power equipment. In order to identify such lightning, we installed measurement systems at two observation sites to measure the E-field waveforms. These were located in the most lightning-prone areas of Japan, and we tried to estimate the amount of charge in lightning flashes from the E- field waveform. In this thesis, we introduced the outline and the results of our electric field (E-field) observations. We also described the effect of applying a digital processing method, and the method of extracting necessary parameters from E-field waveforms.

The main results obtained are shown below:

(1) We investigated the effect of the application of digital integration processing. We were therefore able to confirm that the application of digital integration processing was effective in removing noise and constructing a measurement system with high sensitivity. On the other hand, because the commercial frequency noise can be quite large when applying such digital integration processing, we understand there is a possibility that the accuracy of the system in extracting the E-field change will decrease. In the future, we are measurement parameter extraction process, which may improve the detection accuracy.

(2) As for the automation of the data extraction process, we were able to obtain comparatively good results for the standard E-field waveform. Consequently, increased data processing became possible, and we were able to analyze the data using a statistical method. In the future, it will be necessary to optimize the threshold settings and further decrease the level of noise in order to improve the automatic extraction rate and achieve greater accuracy. Calibration of the E-field antenna in the field may be necessary to ensure data accuracy.

(3) We analyzed the amount of charge in lightning using 6,331 examples, which were obtained by the E-field measuring system and an automatic program for extracting E-field change data using a PC at Nakatsugawa FS (Field-monitoring Stations) during August 2006. As a result, we have come to understand that lightning that about 12% of negative lightning and about 53% of positive lightning exceeds 10C in the summer in Japan.

In our continued E-field observations, various investigations examine the CA (Central Analyzer) processing method shown in Figure 4. In the future, we would like to advance our research toward adding functions for measuring the charge in lightning to LLS.

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