THE RISETIME OF THE ELECTRIC AND THE MAGNETIC FIELD CHANGES
CAUSED BY CLOSE LIGHTNING RETURN STROKES

Y. Oishi, M. Nakano, T. Takeuti and T. Nakai

Research Institute of Atmospherics, Nagoya University
Toyokawa 442

Abstract. The risetime of the electric and magnetic field changes caused by close lightning return strokes is measured using broadband receiving systems. The average risetime is $2.0 \mu\text{s}$ including slow front and $0.25 \mu\text{s}$ excluding slow front for the return strokes within about 5 km from the observation site. From the analysis of the effect of the propagation over a finite conducting earth on the risetime, the risetime of the return stroke current corresponding to the risetime of fast transition of $0.25 \mu\text{s}$ measured at a distance 5 km is estimated to be $0.1 \mu\text{s}$. This value is consistent with the results obtained by Weidman and Krider (1981) who measured the field from return stroke under the condition that the propagation path is entirely over sea water. Based on the data of close lightning return strokes, the amplitude and the steepness of the return stroke currents corresponding to the fast transition are also estimated taking into account the effect of the propagation.

1. Introduction

Recently, the electric and magnetic fields caused by lightning return strokes have been measured with a submicrosecond time resolution, and the fine structure of waveforms caused by return strokes has been discussed by Weidman and Krider (1980) and Krider and Weidman (1983). The risetime of the return stroke current is one of the basic parameters of lightning and is also very important for design of a lightning-protection equipment. Weidman and Krider (1978, 1980) have found that the electric and magnetic fields caused by return strokes begin usually with a slow front which lasts about 2 to 8 μs and are followed by a fast transition to peak, the mean 10-90% risetime of which is about 90 ns. They suggest that it may be necessary to reevaluate the lightning test waveform and the performance of lightning-protection devices because of a submicrosecond component contained in the return stroke current. This letter gives the risetimes of field waveform caused by negative return strokes which struck the ground in Japan and compares them with those of the lightning struck the sea surface. Further, in order to evaluate the effects of the propagation over a finitely conductive earth on the risetime, simple calculations are performed using the equations derived by Wait (1956).

2. Measurements

Electric field changes caused by lightning were measured using a slow and a fast antennas with bandwidths of 0.02 Hz to 100 kHz and 200 Hz to 7 MHz, respectively. Magnetic flux was measured using a single turn loop antenna which had the frequency response from 200 Hz to 3.5 MHz. The outputs of the fast and the loop antennas were digitized every 10 ns with a two-channel 8kW digital-wave-memory and stored on a magnetic disc. The trigger signal for the wave memory was produced by the return stroke signal picked up by the loop antenna, and it was recorded on a two-channel data recorder together with the output of the slow antenna to discriminate the

stroke order in the lightning which triggered the wave memory. The observations were made during the summers of 1984 at Toyokawa and 1985 at Fujioka, Japan.

3. Results

An example of the electric and magnetic field changes caused by a first return stroke which struck the ground within a distance of about 5 km is shown in Figure 1. Figure 1(b) shows the time expansion of the initial portion of the return stroke field changes in Figure 1(a). Figure 1 shows that the rising portion composes of two parts, that is, a slow front and a fast transition, as pointed out by Weidman and Krider (1978). A slow front in a subsequent return stroke often has a shorter rise time and a smaller amplitude than that of a first return stroke, and the risetime of a fast transition is almost the same as that of a first stroke. We measured the 10-90% risetime including the slow front and the 10-90% risetime for the fast transition. The risetimes of fast transitions observed at Toyokawa in 1984 are summarized in Table 1. The distance to a flash is roughly estimated from the arrival time of the thunder. Table 1 indicates that the risetime depends on the distance and it is shorter than 1 μ s for a very close lightning. Figure 2 shows distributions of risetimes of fields from close return strokes within a distance of about 5 km observed at Fujioka in 1985. The risetimes including slow fronts of 35 first-return-stroke fields are found to range from 0.8 to 4.0 μ s as shown in Figure 2(a). On the other hand, in Figure 2(b) the risetimes of fast transitions in 30 first-stroke fields are found to range from 0.1 to 0.5 μ s, and a mean value is 0.25 μ s with a standard deviation of 0.06 μ s.

4. Discussions

4.1. The effect of the propagation on the risetime and the amplitude of the field waveform

Weidman and Krider (1980) reported that a mean risetime of the fast transition was 90 ns for the distant lightning which struck the sea surface and propagation of the field was entirely over sea water. In the present study, the risetime for close lightning is twice or three times larger than the above value. In order to evaluate the

Fig.1. An example of the electric and magnetic field waveforms in a first return stroke.

Table 1. 10-90% risetimes of the fast transition of return stroke fields.

data	distance (km)	E		B	
		No. of data	risetime (μ s)	No. of data	risetime (μ s)
1	2 - 10	5	0.34	5	0.48
2	3 - 15	5	0.74	5	0.75
3	10 - 20	10	1.37	11	1.21
4	20 - 30	19	1.40	22	1.80

Fig.2. Histograms of 10-90% risetimes of fields from first return stroke at a distance of within 5 km, a:including slow front, b:fast transition portion.

effects of the propagation over land, we made simple calculations about the propagation of fields over a finitely conductive earth. A lightning return stroke is considered to be a vertical antenna extending upward above a finitely conductive flat earth. If the antenna is excited by the current, $I(t)$, the vertical electric field, $E(t)$, on the ground at a distance, D , was given by Wait(1956). Cooray and Lundquist (1983) simplified the equation to calculate the radiation field caused by a return stroke as the following,

$$E(t) = \frac{\mu}{2\pi D} \frac{M_0}{\alpha} \exp(-Z^2)$$

where $\alpha^2 = D\epsilon_0/2\sigma C$, $Z = t'/2$, $t' = t - D/c$, σ the conductivity of the ground, c the speed of light in free space, M_0 the current moment, μ the permeability and ϵ_0 the permittivity of free space, respectively. The above equation represents an indicial response of the current moment, $M_0(t)$, so it can be calculated using Duhamel's integral if $M_0(t)$ is given. It is assumed in the present study that the current moment is given by $M(t') = \int_0^{t'} I(h, t') dh$. Adopting the transmission line model for the return stroke current, the current is expressed by $I(h, t') = I_0(\exp(-at'') - \exp(-bt''))$, where $t'' = t' - h/v$ (e.g., Dennis and Pierce, 1964, and Uman and McLain, 1969). v is assumed to be $c/3$. In deriving the above equation, the following assumptions are made: (1) the distance is much larger than the wavelength, (2) the length of the antenna is shorter than the wavelength. In the present case, since the risetime is shorter than $0.5 \mu s$ and the wavelength is regarded as a few hundreds meters, assumption (1) is satisfied even for close lightning at a distance of 1 to 5 km. Since the return stroke velocity is assumed as one third of the speed of light, based on the observations by Idone and Orville (1982) and Nakano et al.(1983), the height of the antenna is less than several tens of meters within a time of $0.5 \mu s$. Thus, assumption (2) is also satisfied. It is noted that the above approximation is only valid for the fast transition of the return stroke waveform. The relationship between the distance and the risetime is shown in Figure 3 for several values of the conductivity, where the ordinate is the risetime, T , normalized to the risetime of the source current, T_0 . Figure 3 shows that the risetime is considerably influenced by both the distance and the conductivity. In Figure 3, with the ground conductivity of $0.006 S/m$, T/T_0 at 5 km is 2.6 which resulting in T of $0.26 \mu s$. We obtain $0.25 \mu s$ for the mean risetime of the fast transition in electric

Fig.3. The relationship between the risetime of the fast transition field and the distance for various ground conductivities.

Fig.4. The relationship between the amplitude of the fast transition field and the distance for various ground conductivities.

Table 2. Observed fast transition electric fields and estimated 10-90% amplitude and steepness of the return stroke currents corresponding to the fast transition.

data No.	distance	E		I		dI/dt (kA/μs)
		risetime (μs)	amplitude (V/m)	risetime (μs)	amplitude (kA)	
1	1.0	0.20	471	0.15	24	160
2	1.0	0.28	371	0.25	20	76
3	3.3	0.27	92	0.16	15	91
4	3.3	0.22	99	0.09	16	173
5	1.6	0.19	218	0.09	23	252
6	1.0	0.30	141	0.27	7	27
7	3.0	0.20	126	0.07	20	287
8	2.3	0.25	372	0.15	39	258
9	3.0	0.32	186	0.23	30	129
10	2.3	0.20	231	0.09	24	268
11	2.0	0.39	278	0.34	28	82
12	1.0	0.24	93	0.21	5	22
13	2.0	0.29	512	0.23	51	222
14	3.3	0.21	164	0.07	25	351
15	3.3	0.29	134	0.18	20	112
mean	2.2	0.25	233	0.17	23	167

fields from first return strokes at a distance of about 5 km. Thus the current risetime is estimated to be about 0.1 μs, which is in consistent with the mean value of 90 ns reported by Weidman and Krider (1981). Figure 4 shows the relationship between the distance and the amplitude of the fast transition field, where the amplitude E is normalized to E_0 which is the amplitude of the electric field propagating over a perfectly conductive earth. The normalized amplitude varies with the conductivity and with the distance.

4.2. The amplitude and the steepness of the return stroke current corresponding to the fast transition

The amplitude and the steepness of the return stroke current can be estimated from the fast transition of the electric field change, based on the calculations given in the previous section. The results are summarized in Table 2, where the conductivity of the ground is assumed to be 0.005 S/m which is a typical value of a wet earth, and dI/dt is defined as the 10-90% current amplitude divided by the 10-90% risetime in the fast transitions. The conductivity of the ground can not be estimated precisely, and it may range from 0.001 to 0.01 S/m depending on the surface condition and the sort of soil (Tsushinkogaku Handbook, 1957). This uncertainty gives the estimation errors of about 30% in the risetime and about 10% in the amplitude. Thus the resultant error introduced in the estimation of the current steepness is roughly 40%. Although the estimation errors are large, Table 2 gives very interesting results. The mean value of the current steepness is 167 kA/ μ s, which is 6 times larger than that by Berger et al. (1975) and almost the same as that by Krider and Weidman (1983). It may be concluded that the risetime and the steepness of currents do not depend on whether the lightning strikes to the open ground or to the sea surface, but they may be affected by high structures such as a TV transmission tower.

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References

- Berger, K., B. Anderson and H. Kroninger, Parameters of lightning flashes, *Electra*, 40, 101-119, 1975
- Cooray, V. and S. Lundquist, Effects of propagation on the risetimes and the initial peaks of radiation fields from return strokes, *Radio Sci.*, 18, 409-415, 1983.
- Dennis, A.S. and E.T. Pierce, The return stroke of the lightning flash to earth as a source of VLF atmospherics, *Radio Sci.*, 68D, 777-794, 1964.
- Idone, V.P. and R.E. Orville, Lightning return stroke velocities in the Thunderstorm Research International Program (TRIP), *J. Geophys. Res.*, 90, 8136-8142, 1982.
- Krider, E.P. and C.D. Weidman, The submicrosecond structure of lightning radiation fields, 69.1-69.8, *Proc. 8th Int. Conf. on Lightning and Static Electricity*, Fort Worth, Texas, 1983.
- Nakano, M., T. Takeuti, Z-I. Kawasaki and N. Takagi, Leader and return stroke velocity measurements in lightning from a tall chimney, *J. Meteor. Soc. of Japan*, 61, 339-345, 1983.
- Tsushinkogaku Handbook, Maruzen, pp.900, 1957.
- Uman, M.A. and D.K. McLain, Magnetic field of lightning return stroke, *J. Geophys. Res.*, 74, 6899-6910, 1969
- Wait, J.R., Transient fields of a vertical dipole over a homogeneous curved ground, *Canadian J. Phys.*, 34, 27-35, 1956.
- Weidman, C.D. and E.P. Krider, The fine structures of lightning return stroke wave forms, *J. Geophys. Res.*, 83, 6239-6247, 1978.
- Weidman, C.D. and E.P. Krider, The submicrosecond risetime in lightning return-stroke fields, *Geophys. Res. Letters*, 7, 955-958, 1980.

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