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Characterization of Far Electric Field Waveforms Produced by Rocket-Triggered Lightning in the Range of 73-126 km

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***Abstract*—In this paper, some characteristics of radiation fields (essentially radiation) waveforms generated by return strokes in rocket-triggered lightning are presented (recorded at a distance ranging from 73 to 126km with field propagation path being over land). The arithmetic mean (AM) geometric mean (GM) value of initial electric field peak normalized to 100 km is 2.9 V/m and 2.7 V/m, respectively. The AM (GM) zero-to-peak risetime, 10-to-90% risetime and half-peak width are 7.7μs (6.3μs), 1.9μs (1.7μs) and 2.9μs (2.7μs), respectively. The AM (GM) initial half-cycle duration, opposite polarity overshoot duration and ratio of electric field peak to opposite polarity overshoot are 50μs (50μs) ,129μs (125μs) and 6.4 (6.3),respectively. The results in this study will be used in examining similarities and dissimilarities between rocket-triggered and subsequent return strokes in natural lightning processes.**

Keywords- far electric field; half-peak width; initial half-cycle duration; rocket-triggered lightning; lightning locating systems

I. INTRODUCTION

Triggered-lightning fields are usually measured within the triggering facility, so that the distances are typically some tens to some hundreds of meters. Electric field waveforms at horizontal distances from the triggered lightning channel attachment point ranging from 0.1 to 1.6 m have been measured with Pockels sensors at the International Center for Lightning Research and Testing at Camp Blanding, Florida had been done by Miki et al (2002). Uman et al. (2000) directly measured the time derivative of the electric field of triggered lightning strokes at distance of 10, 14, and 30 m at the ICLRT, at Camp Blanding, Florida in 1998. Rubinstein et al. (1995), Rakov et al. (2000), Mallick et al (2014), Zhang et al. (2009), measured electric field waveforms of triggered lightning strokes at distance ranging from 30m to 550m.

Le Vine et al. (1989) measured electric field waveforms produced by 28 return strokes in rocket-triggered lightning flashes at a distance of 5.16 km from the Kennedy Space Center (KSC) lightning triggering site, so that the initial portion of the field waveform was essentially radiation. Mallick et al. (2011,2014) recorded far electric field waveforms produced by 69 negative return strokes in 13 flashes triggered using the rocket-and-wire technique at Camp Blanding, Florida, in 2012. The waveforms were recorded at the Lightning Observatory in Gainesville, at a distance of 45 km from the lightning channel.

Far electric field produced by first and first and subsequent return strokes in negative natural lightning flashes where the fields are dominated by their radiation components (at least at early times), has been reported, by Lin et al. (1979), Weidman and Krider (1978), Master et al. (1984), Cooray and Lundquist (1985), Pavlick et al. (2002), Haddad et al. (2012). However, far electric field produced by triggered-lightning field measurements is very rare. Any other well-documented radiation-field measurements for triggered lightning were rarely reported at distances in relatively wide ranges.

In this paper, some characteristics of radiation fields (essentially radiation) waveforms generated by return strokes in rocket-triggered lightning are presented (recorded at a distance ranging from 73 to 126km with field propagation path being over land). Further, since this is the first time that the far electrical fields have been measured in the range of distance 73 km to 126 km in rocket-triggered lightning, we also compare them to their counterparts for subsequent strokes in natural lightning.

II. DATA AND EXPERIMENT

During the summer of 2014, many results of electric field (essentially radiation) have been obtained through artificially-triggering lightning at Guangdong Comprehensive Observation Experiment on Lightning Discharge (GCOELD), including 38 strokes in 8 flashes. A coaxial shunt with 1mΩ resistance and100 kA measurement range was used to measure the current flowing on a grounded lightning rod tied to the triggering wire in classically triggered lightning. These measuring systems and their characteristics are described in detail in Zhang et al (2011, 2012).

Using a time of arrival (TOA) technique, the E-change has been used to determine the (x, y, z, t) locations of return strokes of cloud to ground (CG) and intra-cloud(IC) lighting. At each site of lightning locating system in Foshan (FTLLS), a fast antenna with a decay time constant of 1ms and frequency range of 160 Hz to 1M Hz was equipped. The distance between each

sites and the lightning channel range 68km-126km. Geographical distribution of FTLLS and GECOELD are shown in Fig.1.

After raw data of electric field (essentially radiation) processed in locating system, which consist of 9 sites in Foshan, based on time of arrival (TOA), we choose 5 sites, namely site of LPZ, CCJ, BNZ, JAZ, and MCZ. The distance of these 5 sites between Guangdong Comprehensive Observation Experiment on Lightning Discharge (GCOELD) are 72.4km, 86.3km, 99.6km, 112.3km, and 125.7km, respectively.

The parameters of electric field waveforms, recorded at each satiation, examined in this study are initial electric field peak normalized to 100 km (Ep), zero-to-peak risetime (Tp), 10-to-90 % risetime(T10-90), half-peak width (Thpw), initial half-cycle duration or zero-crossing time (T1), opposite polarity overshoot duration (T2), ratio of electric field peak to opposite polarity overshoot (Ep/Eos). The definitions of the Ep, Tp, Tphw of electric field waveforms, except for the 10-to-90% risetimes, are similar to used in Mallick *et al* (2014).The definitions of TR, T1, T2 and Ep/Eos are similar to used in Haddad et al (2012).

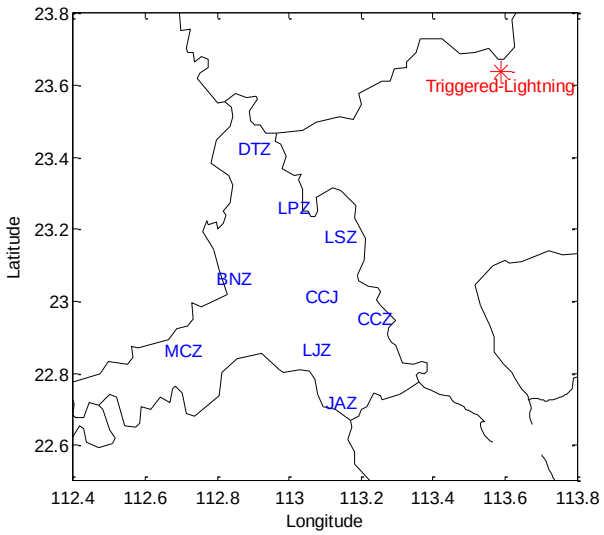

Fig. 1 Distribution of sensors at the lightning locating system in Foshan (FTLLS) and observation experiment sites for lightning.

III. RESULTS

The various far electric field parameters for rocket-triggered lightning return strokes recorded at the CCJ are summarized in Table1 and discussed next.

A. Distance-Normalized Electric Field Peak

The AM (GM) value of initial electric field peak normalized to 100 km for 38 strokes at site of LPZ, CCJ, BNZ, JAZ and MCZ are 2.8V/m (2.0 V/m)，2.9 V/m (2.4 V/m), 3.0V/m (2.7 V/m)，2.7V/m (2.5 V/m) , 2.4V/m (2.0 V/m), respectively (37 RSs recorded at BNZ and LPZ). After averaging above value of each site, the AM and GM distance-normalized electric field peak are 2.9 and 2.5 V/m, respectively.

The GM values for subsequent strokes in natural lightning reported by Rakov et al. (1990) are 2.7 V/m, which stroke flowing previously formed channel. As expected, the value of initial electric field peak normalized to 100 km ,4.1 V/m ,were larger than our values when strokes creating new termination on ground. For comparison, AM values of this parameter for subsequent strokes in natural lightning reported by Lin *et al*. (1979), Cooray and Ludquist *et al*. (1985) are 4.3 V/m and 5.0 V/m, respectively. Haddad et al. (2012) published, due to employed a triggered field measuring system with relatively high thresholds to minimize triggering on cloud discharge pulses ,the responding value, 9.7 V/m (GM), for 349 subsequent strokes were appreciably longer. Our values are somewhat shorter those based on earlier observations. The relatively smaller of GM of peak current in our study (15 kA), probably also be the reason.

B. Waveform Characteristics of Electric field radiation

For 38 return strokes, The AM (GM) zero-to-peak risetime at site of LPZ, CCJ, BNZ, JAZ and MCZ are 8.1μs (6.5μs), 8.1μs (7.2μs), 5.9μs (4.6μs), 8.6μs (6.9μs), and 8.0μs (6.3μs), respectively. After averaging above value of each site, the AM and GM zero-to-peak risetimes are 7.7μs and 6.3μs, respectively.

The AM (GM) 10-to-90 % risetime at site of LPZ, CCJ, BNZ, JAZ and MCZ are 1.8μs (1.6μs), 1.6μs (1.5μs), 2.1μs (1.9μs), 2.0μs (1.9μs), and 1.7μs (1.5μs), respectively. After averaging above value of each site, the AM and GM zero-to-peak risetime are 1.9μs and 1.7μs, respectively.

The AM (GM) half-peak risetime at site of LPZ, CCJ , BNZ, JAZ and MCZ are 3.2μs (2.9μs),2.1μs (2.1μs),2.5μs (2.5μs),3.8μs (3.5μs),and 2.8μs (2.7μs), respectively, with the range of variation from 1.6 to 14.7. After averaging above value of each site, the AM and GM half-peak width were 2.9μs and 2.7μs, respectively.

The AM (GM) of initial half-cycle duration (zero-crossing time) at site of LPZ, CCJ, BNZ, JAZ and MCZ are 53μs (52μs), 47μs (47μs), 44μs (44μs), 54μs (53μs), and 53μs (53μs), respectively. After averaging above value of each site, the AM and GM half-peak width were 50μs and 50μs, respectively. There may be difference in electric field waveforms of each site for the same RS, thus the opposite polarity overshoot was all observed will be choose for statistics.

The AM (GM) value of the opposite polarity overshoots duration at site of LPZ, CCJ, BNZ, JAZ and MCZ are136μs (129μs), 132μs (128μs), 104μs (102μs),144μs (139μs), and 131μs (128μs), respectively, with the range of variation from 70.6μs to 224.3μs. After averaging above value of each site, the AM and GM OPO durations in our study are 129μs and 125μs, respectively.

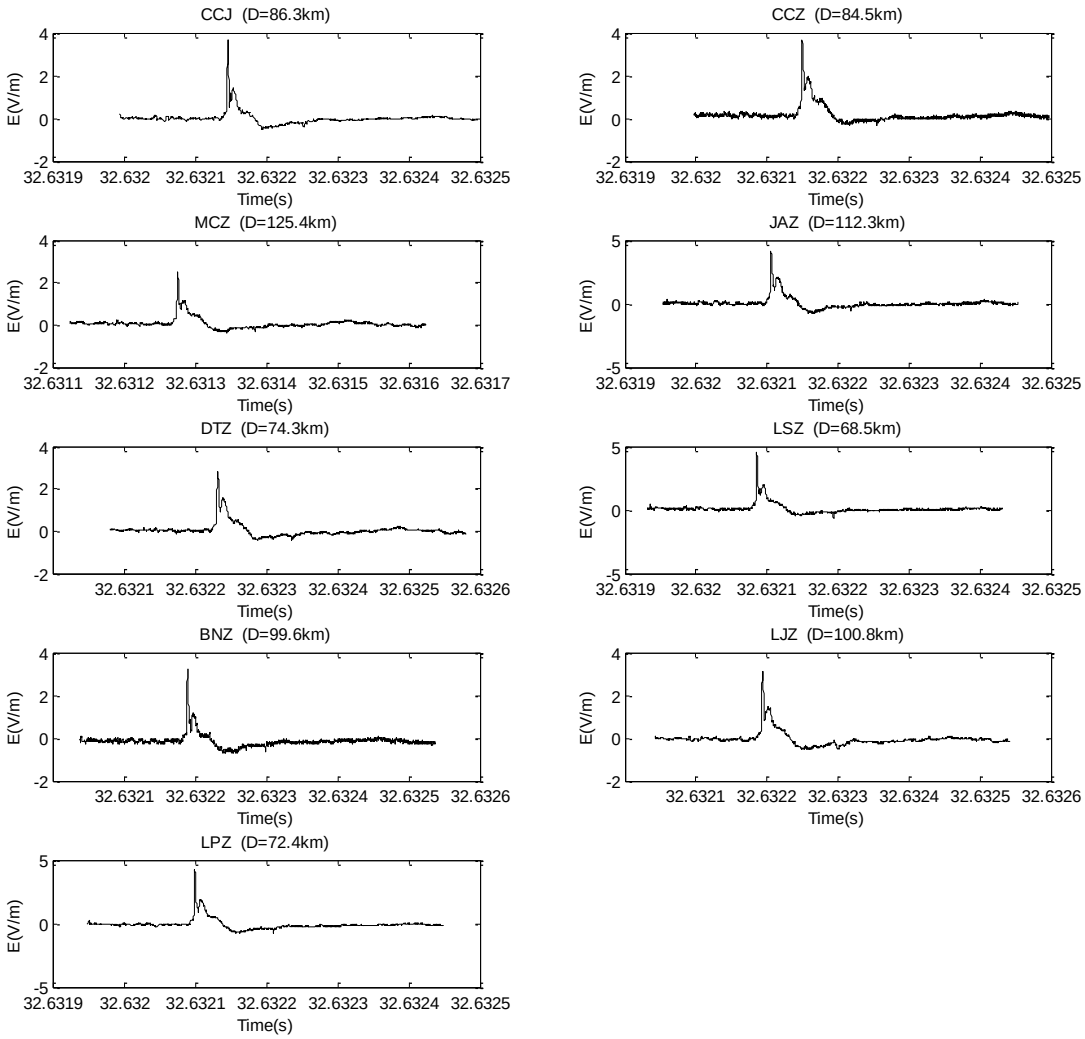

Figure 1. Wideband electric field (E) recorded by 9 sites of lightning locating system in Foshan FTLLS range from 68.5km to 125.4km for 1st return stroke in triggered-lightning flash F0603.The recording length for a flash in each site of FTLLS in 2014 were 500μs.To illustrate different time of arrival of each site, we expands the time (X axis) to 600μs.AS expected, the nearer distance (D) the earlier time of arrival (Time).For example, the Beijing time of the 1st RS in flash F081901 recorded by LSZ (D=68.5km) and MCZ (D=125.4km) were 15:54:32.631932 August 19, 2014 and 15:54:32.632124, respectively

TABLE 1 CHARACTERISTICS OF RADITION ELECTRIC FIELD WAVEFORMS PRODUCED BY ROCKET-TRIGGERED LIGHTNING RECORDED AT SITE OF CCJ WITH DISTANCE OF 86.3KM.

Parameter	Sample size	AM	GM	SD	Median	SD (logx)	Range
Initial electric field peak normalized to 100km(V/m)	38	3.3	2.8	1.6	3.2	0.25	0.7-6.4
zero-to-peak risetime(μs)	38	8.1	7.2	3.6	8.1	0.23	2.4-15.9
10-to-90% risetime(μs)	38	1.8	1.6	0.8	1.3	0.12	1.2-6.2
half-peak widths(μs)	38	2.1	2.1	0.3	2	0.06	1.7-3.4
initial half-cycle duration(μs)	10	47.5	47.2	5.2	45.8	0.05	39.5-45.8
opposite polarity overshoot duration(μs)	10	131.6	127.7	32.8	133.7	0.11	79.5-175
ratio of electric field peak to opposite polarity overshoot	10	7.1	6.9	1.5	7.1	0.1	4.5-9.4

AM=Arithmetic Mean, SD=Standard Deviation, GM=Geometric Mean, SD (logx) =SD of the logarithm to the base10.

TABLE 1 CHARACTERISTICS OF RADITION ELECTRIC FIELD WAVEFORMS PRODUCED BY ROCKET-TRIGGERED LIGHTNING RECORDED AT SITE OF LPZ CCJ BNZ JAZ MCZ WITH DISTANCE FROM 72KM TO 126KM.

Parameter	72.4km(LPZ)		86.3km(CCJ)		99.6km(BNZ)		112.3km(JAZ)		125.7km(MCZ)		Sample size
	AM	GM	AM	GM	AM	GM	AM	GM	AM	GM	
Initial electric field peak normalized to 100km(V/m)	2.8	2.0	2.9	2.4	3.0	2.7	2.7	2.5	2.4	2.0	38
zero-to-peak risetime(μs)	8.1	6.5	8.1	7.2	5.9	4.6	8.6	6.9	8.0	6.3	38
10-to-90% risetime(μs)	1.8	1.6	1.6	1.5	2.1	1.9	2.0	1.9	1.7	1.5	38
half-peak widths(μs)	3.2	2.9	2.1	2.1	2.5	2.5	3.8	3.5	2.8	2.7	38
initial half-cycle duration(μs)	53	52	47	47	44	44	54	53	53	53	10
opposite polarity overshoot duration(μs)	136	129	132	128	104	102	144	139	131	128	10
ratio of electric field peak to opposite polarity overshoot	7.3	7.2	7.1	6.9	6.0	5.9	5.8	5.8	5.8	5.8	10

For comparison, the AM (GM) values for subsequent strokes in natural lightning reported by Haddad et al. (2012) are 64 μs (67μs) and 92 μs (88μs) at distances of 50–100 km and 100–150 km, respectively

The AM (GM) ratio of electric field peak to opposite polarity overshoot at site of LPZ, CCJ, BNZ, JAZ and MCZ are 7.3 (7.2),7.1 (6.9), 6.0 (5.9),5.8 (5.8), and 5.8 (5.8), respectively. After averaging above value of each site, the AM and GM of this parameter were 6.4 and 6.3, respectively.

For comparison, the AM (GM) values for subsequent strokes in natural lightning reported by Haddad et al. (2012) are 6.7 (6.1) and 5.8 (5.3) at distances of 50–100 km and 100–150 km, respectively. Our values are comparable than those reported by Haddad et al. Similarly, the responding values in Mallick *et al* (2014) at the distance of 45km are 15.9 and 15.5, respectively. The difference is probably related to different current and speed profiles along the lightning channels.

IV. SUMMARY

In this paper, some characteristics of radiation fields waveforms generated by return strokes in rocket-triggered lightning are presented. This is the first detailed characterization of radiation electric field waveforms produced by rocket-triggered lightning at distance ranging from 73km to 126km. We examined the data measured at LPZ, CCJ, BNZ, JAZ, and MCZ. The distance between the lightning channel and each site are 72.4km, 86.3km, 99.6km, 112.3km and 125.4km, respectively. Our study expands work of Mallick's (2014) (recorded the far electric field produced by rocket-triggered at 45km). The founding may as follow: (1) The arithmetic mean (AM) geometric mean (GM) value of initial electric field peak normalized to 100 km is 2.9 V/m and 2.7 V/m, respectively. (2) The AM (GM) zero-to-peak risetime, 10-to-90% risetime and half-peak width are 7.7μs (6.3μs), 1.9μs (1.7μs) and 2.9μs (2.7μs), respectively. (3) The AM (GM) initial half-cycle duration, opposite polarity overshoot duration and ratio of electric field peak to opposite polarity overshoot are 50μs (50μs) ,129μs (125μs) and 6.4 (6.3), respectively. The results in this study will be used in examining similarities and dissimilarities between rocket-triggered and subsequent return strokes in natural lightning processes.

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