Characterization of magnetic field waveforms from triggered lightning attached on transmission line at 18 m, 130 m and 1.55 km

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Abstract
The authors present a statistical analysis of characteristics of magnetic fields at different distances from triggered lightning experiments on Transmission Line at Guangdong Comprehensive Observation Experiment on Lightning Discharge during the summer of 2019. The histograms and parameters of statistical distributions for the following 22 waveform characteristics are presented, including current peak, 10%–90% risetime, half-peak width and steepness, leader magnetic field peak, return-stroke magnetic field peak, magnetic field peak, 10%–90% risetime, half-peak width and steepness at 15 m, 130 m and 1.55 km. The arithmetic mean of 48 return stroke current peaks is 18.3 kA and the geometric mean is 17.0 kA. The arithmetic and geometric means of the current 10%–90% risetime are 0.6 and 0.6 μs, respectively. The leader magnetic field, return-stroke magnetic field and magnetic field peak at 18 m, 130 m and 1.55 km are shown linear relationship with current peak values. With increasing the distance(r), the magnetic field peak value decrease, combining the magnetic field characteristics reported by previous studies, the analysis of all magnetic field peaks in different distances suggest linear relationship with \( r^{-0.90} \). The magnetic field 10%–90% risetime shows linear relationship with \( \ln(r) \) and half-peak width did not show significant correlation with distance.

1 INTRODUCTION

Statistical characteristics of the electromagnetic fields from close lightning are needed for proper assessment of its influence on transmission line. Rocket-triggering lightning technique can make lightning occur at a predictable time and position. We can directly measure the current at the bottom of the lightning channel and close electromagnetic fields to study lightning protection design and examine the return stroke (RS) models [1–4].

Krider et al. [5] made first broadband antenna system to measure the magnetic field caused by distant lightning. Lin et al. [6] reported electric and magnetic field waveforms produced by first and subsequent RSs in negative natural lightning flashes in Florida at distances ranging from 1 to 200 km. Rakov et al. [7] provided new insights into the lightning discharge processes by using the synchronous data of channel base currents and electromagnetic fields at different distances from the channel. Uman et al. [8] discussed the correlated time derivatives of current, electric field intensity and magnetic flux density for triggered lightning at 15 m and their results show that the similarity between the measured electric field, magnetic field and current derivatives for the initial 150 ns is not due to a dominant radiation field. Schoene et al. [9] further presented statistical characteristics of the electric and magnetic fields and their time derivatives 30 m from triggered lightning at Camp Blanding, Florida. Statistical distributions of close magnetic fields and channel base currents were also discussed based on data obtained in Shandong Artificially Triggering Lightning Experiment (SHATLE) by using the rocket-triggering lightning technique [10–13].

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The difference in parameter characteristics of magnetic field waveform may be due to the height of the lightning rod, the strike object grounding and the field propagation path. The experimental site was covered by sand at Camp Blanding in Florida and the height of the metal rod above the ground surface was 6 and 10 m, while 20 m at Kennedy Space Center [14, 15]. Since 1999, the height of the lightning rod is changed 1–2 m at Camp Blanding. The launcher was placed underground in the centre of a 4 × 4 m pit with the top of the launcher flush with the ground surface and the underground launcher was located at the centre of a 70 × 70 m mesh grid that was covered by sand [16]. The strike rod in SHATLE was 5 m high [17]. The strike rod in Guangdong Comprehensive Observation Experiment on Lightning Discharge (GCOELD) installed at the insulating tower which was 12 m high and was connected to transmission line in order to research the lightning protection characteristics overhead transmission line [18, 19].

In this study, we show histograms, along with statistical summaries, for the following 22 parameters of current and magnetic field: current peak, 10%–90% risetime, half-peak width and steepness, leader magnetic field peak, return-stroke magnetic field peak, magnetic field peak, 10%–90% risetime, half-peak width and steepness at 15 m, 130 m and 1.55 km at GCOELD during the summer of 2019. We also compare our results with those observed from other triggered lightning experiments.

2 | MEASUREMENT AND DATA

2.1 | Experiment arrangement

The experiment was carried out in GCOELD during the summer of 2019. As shown in Figure 1, we made synchronous observations for the triggered lightning, including the channel-base current, optical image of high-speed video camera (Phantom Miro M310), and magnetic field measurement at the distances of 18 m, 130 m and 1.55 km; the inset shows the image for the rocket-triggering lightning at 15:21:23 UTC on 2 July 2019. Lightning was triggered to a 12-m-high lightning rod connected to transmission line. The channel-base current was measured by a coaxial shunt with a resistance of 1 mΩ. The current signal was transmitted to the control room 130 m away from the rocket launcher with a fibre transmission system. The current signal and the electromagnetic field signal at 130 m were synchronously recorded by a multi-channel high-speed digital oscilloscope placed in control room (DL850) with a sampling rate of 50 MHz (sampling interval of 20 ns) and a recording length of 2 s. The bandwidth of current measurement system is 20 MHz. The magnetic field measurement at 130 m was set to be at about 3.5 m above ground. The magnetic field signal at 18 m was recorded by a computer acquisition system at 10 MHz sampling rate and with a recording length of 1 s. The magnetic field measurement at 18 m was set to be at about 1.5 m above ground. The third magnetic field measurement was installed at the about 15-m-high house roof 1.55 km away from the lightning triggering site. The output of magnetic field measurement at 1.55 km was recorded with a data acquisition system at 10 MHz sampling rate and with a recording length of 1 s.

Meanwhile, the frequency response has been measured in the laboratory for the magnetic field measurement used in the observation. The 3 dB bandwidth of the magnetic field measurement is 40–800 kHz.

2.2 | Data

During the summer of 2019, 48 RSs in eight triggered flashes had been observed. Eight lightning flashes were named as Tr_201901 to Tr_201908, and Table 1 gives the detail information of eight events. Each of the eight lightning flashes included multiple RSs and the number of RSs ranged from 2 to 11. The average number of RSs for eight lightning flashes was 6. All RSs in this study delivered negative charge to ground. Magnetic field at 18 m was recorded for five triggered flashes except for Tr_201901, Tr_201902 and Tr_201903. For some high-intensity lightning signals, magnetic field signal at 18 m showed varying degrees of saturation. For the 18-m distance, we analysed 12 unsaturated RSs. Magnetic field at 130 m was all recorded by the oscilloscope for eight triggered flashes and magnetic field at 1.55 km was recorded for four triggered flashes from Tr_201905 to Tr_201908, including 27 RSs.

3 | RESULTS

The following results are based on data for eight triggered flashes, including 48 RSs. Note that for the current and the magnetic fields, the polarity of the waveforms is ignored and only absolute values are given in the following histograms and table presented here. Definitions of current waveform and magnetic field waveform parameters are follows.

Figure 2 shows an example of a measured current waveform. It usually exhibits a fast rise to peak and then decay. A 10%–90% risetime and half-peak width are measured and presented for the RS current. In addition, the 10%–90% average steepness of the current rising from 10% peak value to 90% peak value in the RS current waveform is also measured.

Typical magnetic field waveform with respect to time for 18 m, 130 m and 1.55 km, is shown in Figure 3. It usually exhibits a relative slow initial front followed by a fast rise to peak and then decay. As the downward leader tip approaches ground, the magnetic field on ground associated with the leader increases with time. When the leader attaches to the ground, RS is initiated. Therefore, the current increases abruptly and there is a fast rise in magnetic field. A slow rise part corresponding to leader is labelled $B_L$ and steep rise part corresponding to the RS is labelled $B_{RS}$ and $B = B_L + B_{RS}$. Other definitions of magnetic field waveform parameters, including 10%–90% risetime, half-peak width and 10%–90% steepness, can be also found in Schoene et al. [9], Kodali et al. [20], Wang et al. [21]. Note that a 10%–90% risetime, half-peak width and 10%–90% steepness all occurs on the stage of RS.
Histograms of current peak, current 10%-90% risetime, current half-peak width and current 10%-90% steepness are found in Figure 4. Forty-eight RSs current were analysed.

The arithmetic mean (AM) of 48 RS current peaks measured in GCOELD during the summer of 2019 is 18.3 kA and the geometric mean (GM) is 17.0 kA, respectively. The arithmetic and GMs of the current 10%-90% risetime are 0.6 and 0.6 μs, respectively. The current half-peak width presented an AM of 12.8 μs and GM of 9.8 μs for 48 values measured at the GCOELD, respectively. In addition, we calculated current 10%-90% average steepness. The AM and GM are 25.5 kA/μs and 23.0 kA/μs, respectively.

### 3.2 Magnetic field at 18 m

For the 18-m distance, when the lightning signal is strong, magnetic field signal recorded computer acquisition system may be saturated. Therefore, we selected twelve unsaturated RSs. Histograms are presented for the following parameter defined in Figure 3: leader magnetic field peak, return-stroke magnetic field peak, magnetic field peak, magnetic field
10%–90% risetime, magnetic field half-peak width and magnetic field 10%–90% steepness, as shown in Figure 5. The AM and GM of leader magnetic field at 18 m are 9.4 and 8.3 μT, respectively. For the leader peak magnetic field, it might be affected by the height of sensor. The AM and GM of return-stroke magnetic field at 18 m are 142.7 and 140.4 μT, respectively. The arithmetic and GMs of the magnetic field peak at 18 m in our study data are 147.5 and 145.1 μT, respectively.

The arithmetic and GMs of the magnetic field 10%–90% risetime at 18 m in our study data are 2.1 and 2.0 μs, respectively. The minimum value (Min) is greater than 1 μs, but according to the statistical parameters of current risetime in the Section 3.1, the magnetic field 10%–90% risetime may be less than 1 μs in the very near distance of 18 m. The upper cut-off frequency of the magnetic field sensor is 800 kHz, Therefore, the magnetic field of fast rising currents cannot be resolved sufficiently.

The arithmetic and GMs of our magnetic field half-peak widths measured at 18 m are 13.3 and 11.2 μs, respectively. In addition, magnetic field 10%–90% average steepness was calculated. The AM and GM are 57.1 T/s and 54.5 T/s at 18 m.

3.3 | Magnetic field at 130 m

Histograms of leader magnetic field peak, return-stroke magnetic field peak, magnetic field peak, 10%–90% risetime, magnetic field half-peak width and magnetic field 10%–90% steepness at 130 m are found in Figure 7. Forty-eight return-stroke magnetic field were analysed.

The AM and GM of leader magnetic field at 130 m are 7.1 and 4.3 μT, respectively (n = 48, min = 0.2 μT, max = 22.2 μT, standard deviation (SD) = 5.7 μT), while the AM and GM of return-stroke magnetic field at 130 m are 47.4 and 42.0 μT, respectively (n = 48, min = 12.2 μT, max = 118.2 μT, SD = 23.2 μT). The arithmetic and GMs of the magnetic field peak at 130 m in our study data are 54.5 and 47.7 μT, respectively (n = 48, min = 12.5 μT, max = 120.9 μT, SD = 27.2 μT).

The fitting relationship between return-stroke current and leader magnetic field, return-stroke magnetic field, and magnetic field peak at 130 m are shown in Figure 8. The current peak values were found to show linear relationship with $B_L$, $B_{RS}$ and $B$, the regression equation being $B_L = -5.02 + 0.72 I_{Meas}$, $B_{RS} = -3.56 + 2.8 I_{Meas}$ and $B = -7.96 + 3.35 I_{Meas}$, where the units of magnetic field and current are μT and kA, and the determination coefficient ($R^2$) being 0.79, 0.78 and 0.83, respectively.

The arithmetic and GMs of the magnetic field 10%–90% risetime are 4.5 and 4.5 μs (Min 4.1 μs, maximum value [Max] 5 μs) for 48 values measured at 130 m. The arithmetic and GMs of the magnetic field half-peak width are 37.6 and 35.1 μs (Min 23.2 μs, Max 127.1 μs), respectively. And the AM and GM of the steepness are 8.4 T/s and 7.4 T/s (Min 2.1 T/s, Max 21.5 T/s), respectively.

3.4 | Magnetic field at 1.55 km

Histograms of leader magnetic field peak, return-stroke magnetic field peak, magnetic field peak, 10%–90% risetime, magnetic field half-peak width and magnetic field 10%–90% steepness, as shown in Figure 9. The AM and GM of leader magnetic field at 1.55 km are 7.1 and 4.3 μT, respectively (n = 48, min = 0.2 μT, max = 22.2 μT, standard deviation (SD) = 5.7 μT), while the AM and GM of return-stroke magnetic field at 1.55 km are 47.4 and 42.0 μT, respectively (n = 48, min = 12.2 μT, max = 118.2 μT, SD = 23.2 μT).

The fitting relationship between return-stroke current and leader magnetic field, return-stroke magnetic field, and magnetic field peak at 1.55 km are shown in Figure 10. The current peak values were found to show linear relationship with $B_L$, $B_{RS}$ and $B$, the regression equation being $B_L = -5.02 + 0.72 I_{Meas}$, $B_{RS} = -3.56 + 2.8 I_{Meas}$ and $B = -7.96 + 3.35 I_{Meas}$, where the units of magnetic field and current are μT and kA, and the determination coefficient ($R^2$) being 0.79, 0.78 and 0.83, respectively.

The arithmetic and GMs of the magnetic field 10%–90% risetime are 4.5 and 4.5 μs (Min 4.1 μs, maximum value [Max] 5 μs) for 48 values measured at 1.55 km. The arithmetic and GMs of the magnetic field half-peak width are 37.6 and 35.1 μs (Min 23.2 μs, Max 127.1 μs), respectively. And the AM and GM of the steepness are 8.4 T/s and 7.4 T/s (Min 2.1 T/s, Max 21.5 T/s), respectively.
steepness at 1.55 km are found in Figure 9. Twenty-seven return-stroke magnetic field were analysed.

For 1.55-km distance, magnetic field signal has become weak. The AM and GM of leader magnetic field at 1.55 km are 0.1 and 0.1 μT, respectively, while the AM and GM of return-stroke magnetic field are 1.7 and 1.5 μT, respectively. The arithmetic and GMs of the magnetic field peak in our study data are 1.8 and 1.6 μT, respectively.

The fitting relationship between return-stroke current and leader magnetic field, return-stroke magnetic field, and magnetic field peak at 1.55 km are shown in Figure 10. The current peak values were found to show linear relationship with $B_L$, $B_{RS}$ and $B$, the regression equation being $B_L = -0.09 + 0.01 I_{\text{Meas}}$, $B_{RS} = 0.26 + 0.07 I_{\text{Meas}}$ and $B = -0.03 + 0.1 I_{\text{Meas}}$, where the units of magnetic field and current are μT and kA, and the determination coefficient ($R^2$) being 0.59, 0.71 and 0.63, respectively.

Our magnetic field 10%–90% risetime AM and GM are 9.6 and 9.2 μs, respectively. The arithmetic and GMs of our magnetic field half-peak widths measured at 1.55 km are 33.9 and 30.4 μs, respectively. In addition, the AM and GM of steepness are 0.15 T/s and 0.13 T/s at 1.55 km, respectively.

4 | DISCUSSION

In this section, there have been a number of previous measurements of triggered lightning RS current characteristics, including Camp Blanding (Florida), Kennedy Space Center (Florida), Saint-Privat d’Allier (France), SHATLE (China) with which our data on current at the GCOELD can be compared. Qie et al. [22, 23], reported a slightly lower AM of 14.3 kA and GM of 12.1 kA for 36 values measured at the SHATLE. Depasse et al. [24], found the same AM of 14.3 kA for 305
values measured at the Kennedy Space Center, Florida and a lower AM of 11.0 kA for 54 values measured at Saint-Privat d’Allier, France. Rakov et al. [7], Crawford et al. [25], Uman et al. [8] and Schoene et al. [26], reported an AM of 15.1 kA and GM of 13.3 kA, 12.8 and 11.7 kA, 13.9 and 12.2 kA from measurements at Camp Blanding in 1993, 1997, 1998, and 1999–2004, respectively. The AM and GM of the peak current are distinctly larger than those reported by other authors. This could be attributable to the different storm types, local topography, different geographical locations and grounding resistance.

Our current 10%-90% risetime is significantly lower than those found by Qie et al. of 2.0 and 1.9 μs for 36 current waveforms at SHATLE, and by Schoene et al. of 1.2 and 0.9 μs for 81 waveforms measured at Camp Blanding, Florida from 1999 to 2004. Also, our data are less than those measured by Depasse et al. at Saint-Privat d’Allier, France (AM = 1.14 μs). However, the arithmetic and GMs of our current 10%-90% risetime was close to those measured at Camp Blanding, Florida in 1997 by Crawford et al. (AM = 0.9 μs, GM = 0.6 μs). It follows from the above that our current waveforms are apparently “sharper” than the current waveforms observed by others.

Crawford et al. and Schoene et al. presented an AM of 35.7 μs and GM of 29.4 μs of current half-peak width for 11 values, and AM of 23 μs and GM of 19 μs for 142 waveforms at Camp Blanding, Florida in 1997 and 1999–2004, respectively. Qie et al. reported a slightly lower AM of 23.7 μs and GM of 14.8 μs for 36 values measured at the SHATLE. However, the AM of current half-peak width measured at Saint-Privat d’Allier, France by Depasse et al. is 49.8 μs. Note that our arithmetic and GMs of current half-peak width are distinctly lower than those reported by other authors.
We measured magnetic fields at distances of 18 m, 130 m and 1.55 km. The statistical parameters for magnetic fields are presented in Table 2 and were compared with those measured by Crawford et al. at 5.5 and 10.3 m, by Schoene et al. at 15 and 30 m in 1999 and 2000 at Camp Blanding, Florida, and by Yang et al. at 60 m at the SHATLE from 2005 to 2009, where \( n \) denotes the sample size. Calculated statistical parameters are: Min, Max, AM, GM and SD.

The AM and GM of the ratio between 12 magnetic field peaks simultaneously measured at 18 m and 130 m at the GCOELD are 5.9 and 5.6 (SD = 2.4), respectively. The ratio between 27 magnetic field peaks simultaneously measured at 130 m and 1.55 km at the GCOELD are 28.5 and 27.1 (SD = 8.8), respectively. The arithmetic and GMs of the magnetic field peak, measured by Crawford et al. at 5.5 m, are 470 and 418 μT, respectively. For 10.5-m distance, they are 230 and 212 μT, respectively. Schoene et al. presented the AM of 203 μT and GM of 182 μT for 92 values measured at 15 m and the AM of 1.8 μT and GM of 1.6 μT for 88 values measured at 30 m. The analysis of all magnetic field peaks suggests a distance dependence of \( r^{0.90} \), as shown in Figure 11. With increasing the distance, the magnetic field peak value decrease.

For closer magnetic field, Crawford et al. presented the AM GM of magnetic field 10%-90% risetime at 5.5 m and 10.3 m all are 0.8 and 0.6 μs, respectively, as shown in Table 2. They are significantly lower than our magnetic field 10%-90% risetime at 18 m (AM = 2.1 μs, GM = 2.0 μs) and AM of 3.2 μs and GM of 2.5 μs at 60 m for 32 values measured at the SHATLE. It is found that magnetic field 10%-90% risetime increase with increasing the distance, as shown in Figure 12. The analysis of all magnetic field 10%-90% risetime suggests a distance dependence of ln(r).
Crawford et al. presented an AM of 25.8 μs and GM of 22.5 μs of magnetic field half-peak width for 11 values measured at 5.5 m, and AM of 26.2 μs and GM of 20.9 μs for 10 waveforms measured at 10.3 m at Camp Blanding, Florida in 1997. Schoene et al. reported that the arithmetic and GMS are 17.4 and 14.9 μs for 15-m distance, and 14.6 and 12.5 μs for 30-m distance. Yang et al. described magnetic field half-peak width for 32 values at 60 m at the SHATLE. Taking into account our magnetic field half-peak widths, half-peak width did not show significant correlation with distance, as evident in Table 2. In addition, comparison of our magnetic field 10%-90% steepness at different distances shows that the closer the distance, the greater the steepness.

Mosaddeghi et al. [27], reported magnetic fields from leaders and RSs associated with lightning strikes to the 100 m tall Gaisberg tower in Austria obtained in 2007 and 2008. The fields were measured at a distance of about 20 m from the tower. The mean of magnetic field peak was 158.9 μT for 76 values (Min = 40.6 μT, Max = 365.7 μT). They were similar with our magnetic field peak at 18 m. Pavanello et al. [28], presented the magnetic field measured simultaneously at distances of 2.0, 16.8 and 50.9 km from the CN Tower. The AMs of magnetic field peak are 1.079 μT for 31 values at 2.0 km, 0.1208 μT for 14 values at 16.8 km, and 0.0421 μT for 22 values at 50.9 km. This is also consistent with the observations that with increasing the distance, the magnetic field peak value decrease.
| Location/Year | Distance | $n$ | Min | Max | AM  | GM  | SD  |
|--------------|----------|-----|-----|-----|-----|-----|-----|
| **Leader magnetic field peak, μT** | | | | | | | |
| This study   | 18 m     | 10  | 3.0 | 9.7 | 5.7 | 5.4 | 2.2 |
| This study   | 130 m    | 48  | 0.2 | 22.2| 7.1 | 4.3 | 5.7 |
| This study   | 1.55 km  | 27  | 0.01| 0.5 | 0.1 | 0.1 | 0.1 |
| **Return-stroke magnetic field peak, μT** | | | | | | | |
| This study   | 18 m     | 12  | 99.9| 181.6| 142.7| 140.4| 26.2 |
| This study   | 130 m    | 48  | 12.2| 118.2| 47.4 | 42.0 | 23.2 |
| This study   | 1.55 km  | 27  | 0.7 | 4.0 | 1.7  | 1.5  | 0.8  |
| **Magnetic field peak, μT** | | | | | | | |
| Camp Blanding, Florida; 1997 [25] | 5.5 m | 11  | 150 | 874 | 470 | 418 | 223 |
| Camp Blanding, Florida; 1997 [25] | 10.3 m | 10 | 91 | 377 | 230 | 212 | 93  |
| Camp Blanding, Florida; 1999–2000 [9] | 15 m | 93 | 53 | 466 | 203 | 182 | 95  |
| Camp Blanding, Florida; 1999–2000 [9] | 30 m | 88 | 27 | 239 | 109 | 98  | 50  |
| SHATLE; 2005–2009 [10] | 60 m | 32 | 18 | 148 | 62  | 52  | 36  |
| This study   | 18 m     | 12  | 103.5| 181.6| 147.5| 145.1| 26.9 |
| This study   | 130 m    | 48  | 12.5| 120.9| 54.5 | 47.7 | 27.2 |
| This study   | 1.55 km  | 27  | 0.7 | 4.1 | 1.8  | 1.6  | 0.9  |
| **Magnetic field 10%–90% risetime, μs** | | | | | | | |
| Camp Blanding, Florida; 1997 [25] | 5.5 m | 11 | 0.3 | 2.7 | 0.8 | 0.6 | 0.8 |
| Camp Blanding, Florida; 1997 [25] | 10.3 m | 10 | 0.3 | 3.2 | 0.8 | 0.6 | 0.9 |
| SHATLE; 2005–2009 [10] | 60 m | 32 | 0.4 | 8.4 | 3.2 | 2.5 | 2.25 |
| This study   | 18 m     | 12  | 1.2 | 3.1 | 2.1  | 2.0  | 0.6  |
| This study   | 130 m    | 48  | 4.1 | 5   | 4.5  | 4.5  | 0.2  |
| This study   | 1.55 km  | 27  | 6.8 | 23.2| 9.6  | 9.2  | 3.3  |
| **Magnetic field half-peak width, μs** | | | | | | | |
| Camp Blanding, Florida; 1997 [25] | 5.5 m | 11 | 7.7 | 65.8| 25.8| 22.5| 15.2 |
| Camp Blanding, Florida; 1997 [25] | 10.3 m | 10 | 5.1 | 78.3| 26.2| 20.9| 20.4 |
| Camp Blanding, Florida; 1999–2000 [9] | 15 m | 92 | 4.1 | 43.4| 17.4| 14.9| 9.1  |
| Camp Blanding, Florida; 1999–2000 [9] | 30 m | 88 | 3.4 | 37.1| 14.6| 12.5| 7.9  |
| SHATLE; 2005–2009 [10] | 60 m | 32 | 1 | 31  | 12.7| 10.28| 7.07 |
| This study   | 18 m     | 11  | 5.5 | 44.3| 13.3| 11.2| 10.7 |
| This study   | 130 m    | 48  | 23.2| 127.1| 37.6| 35.1| 18.6 |
| This study   | 1.55 km  | 27  | 11.1| 69.0| 33.9| 30.4| 15.3 |
| **Magnetic field steepness, T/s** | | | | | | | |
| This study   | 18 m     | 12  | 30.7| 81.7| 57.1| 54.5| 17.5 |
| This study   | 130 m    | 48  | 2.1 | 21.5| 8.4 | 7.4 | 4.1  |
| This study   | 1.55 km  | 27  | 0.04| 0.33| 0.15| 0.13| 0.08 |

Abbreviations: AM, arithmetic mean; GM, geometric mean.
We examined current and magnetic field waveforms with sensitivities from rocket-triggered lightning in 18 m, 130 m and 1.55 km range through three-station observations. This study will extend magnetic field database of different distance. The presented results are compared to previous reports of RSs of artificially triggered lightning.

The statistical data are summarised in the form of histograms. The AM of 48 RS current peaks is 18.3 kA and the GM is 17.0 kA. The arithmetic and GMs of the current 10%–90% risetime are 0.6 and 0.6 μs, respectively. Our current half-peak width presented an AM of 12.8 μs and GM of 9.8 μs. The AM and GM of current 10%–90% average steepness are 25.5 and 23.0 kA/μs, respectively.

The leader magnetic field, return-stroke magnetic field and magnetic field peak at 18 m, 130 m and 1.55 km are shown linear relationship with current peak values. With increasing the distance, the magnetic field peak value decrease, the analysis of all magnetic field peaks in different distances suggest linear relationship with $r^{-0.90}$. The magnetic field 10%–90% risetime increase with increasing the distance, and show linear relationship with ln(r). However, half-peak width did not show significant correlation with distance.

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