Characteristics of channel base currents and close magnetic fields in triggered flashes in SHATLE

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Statistical distributions of channel base currents and close magnetic fields have been investigated by using data measured during Shandong Artificially Triggering Lightning Experiment (SHATLE) from 2005 to 2009. Effects of different factors on close magnetic fields have been examined by using numerical method. Statistical results showed that return stroke peak currents varied from 5.8 kA to 45.7 kA with a geometric mean (GM) of 14.1 kA. The GM of 10–90% risetime, 30–90% risetime, and half-peak width in current waveforms were consistent with most of the results found in the literature. The magnetic fields at 60 m, based on 32 return strokes, varied from 18 μT to 148 μT with a GM of 52 μT. The peak value of the 10–90% risetime in magnetic field waveform was between 1 and 2 μs with a minimum of 0.4 μs and a maximum of 8.4 μs, covering a relatively wide range compared with other studies. The numerical modeling results showed that for larger return stroke speeds, the magnetic field peaks are larger, half-peak widths and risetimes are smaller. Effects of distance on time-variation contribution of induction and radiation components are quite different from that of return stroke speed and current risetime. With increasing the distance or current risetime, the magnetic field peak decreases, but the risetime and half-peak width increase.


1. Introduction

Accurate characterization of close electromagnetic fields produced by lightning plays an important role in the assessment of its influence on electronic systems. Since the probability for a natural lightning to strike a given point on the Earth’s surface is very low, measurement of lightning produced electromagnetic fields are difficult. The so-called rocket-and-wire triggering lightning technique is a useful tool for studying both the direct and the induced effects of lightning. In most aspects the triggered lightning is a controllable analog of natural lightning [e.g., Rakov et al., 2005; Qie et al., 2009]. Therefore close electromagnetic fields and channel base currents from triggered lightning are of considerable value. Since the first triggered lightning discharges in 1960s off the west coast of Florida [Newman et al., 1967], the artificially triggered lightning experiments have been taken place in many regions of the world, such as in France [Fieux et al., 1975], in the United States [e.g., Fisher et al., 1993; Hubert et al., 1984; Morris et al., 1994; Rakov et al., 1998; Rakov et al., 2005; Uman et al., 1997; Willett, 1992], in Japan [e.g., Horii, 1982; Kito et al., 1985; Nakamura et al., 1992; Nakamura et al., 1991], in China [e.g., Liu et al., 1994; Qie et al., 2007], and in Brazil [e.g., Pinto et al., 2005; Saba et al., 2005], etc. Owing to the limitation of the article pages, it is difficult to discuss each paper cited here in detail. It is worth noting that the first triggered flash over land was accomplished in France [Fieux et al., 1975]. And the United States have made a great contribution to the triggered-lightning studies.

Early studies aiming at the investigation of close electromagnetic fields could be found in many papers. Rubenstein et al. [1995] analyzed the vertical electric field at 500 m and 30 m from triggered flashes and found that the leader-return stroke field waveforms appear as asymmetrical V-shaped pulses, with the bottom of the V being associated with the transition from the leader to the return stroke; Rakov et al. [1998] provided 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. [2002] discussed the correlations between time derivatives of current, electric field, and magnetic field by using the triggered flash data and numerical
method, and their results show that the similarity between the
measured electric field, magnetic field, and current deriva-
tives for the initial 150 ns is not due to a dominant radiation
field. Statistical distributions of electric and magnetic fields
and their derivatives were reported by Schoene et al. [2003a].
There are also some other papers [e.g., Crawford et al., 2001;
Miki et al., 2002; Kodali et al., 2005; Schoene et al., 2003b;
Leteinturier et al., 1990; Zhang et al., 2009] on electro-
magnetic fields of triggered flashes and will not be reviewed
in detail. All these researchers provided a number of new
insights into the various lightning processes and effects, but
statistical characteristics of close magnetic fields are rela-
tively few compared with that of electric fields and channel
base currents. Moreover, studies aiming at the investigation
of effects of different factors on close magnetic fields were
not commonly found in the literature.

[4] The statistical distributions of close magnetic fields and
channel base currents discussed here were based on data
obtained in Shandong Artificially Triggering Lightning
Experiment (SHATLE) experiments by using the rocket-and-
wire technique from 2005 to 2009. The SHATLE exper-
iments are performed in Shandong province, which is located
in eastern China and very close to the Bohai Sea [e.g., Qie
et al., 2007]. This experiment has been carried out since the
summer of 2005 and continued during the summer of 2006
through 2009. During the 5 years, classical and altitude trig-
gerating techniques have been used. The rockets used from
2005 to 2008 were made of steel, and specially designed
rocket used in 2009 were made of composite material with
better safety [Qie et al., 2010]. In this paper, statistical char-
acteristics of close magnetic fields and channel base currents
in triggered flashes are analyzed and compared with other
studies in detail. In addition, effects of different factors on
close magnetic fields are investigated by using numerical
method.

2. Experiment Description

[5] Two observation sites were established during the
SHATLE experiment. Site 1 (the control room) was located
60 m away from the launching site, while Site 2 (the main
observation site) was located 550 m away. The instrumenta-
tions that have been used from 2005 to 2008 could be found in
the work of Qie et al. [2007]. In 2009, new instruments have
been used in SHATLE experiment. A current monitor with a
bandwidth of 0.9 Hz to 1.5 MHz and a 0.5 mΩ shunt with
bandwidth of 0–3.2 MHz have been used to measure the
channel base current. It should be noted that the 1.5 MHz
bandwidth may affect the accuracy of the derived measure-
ments in some extent. The current signals have been trans-

Figure 1. (a, d) Pulse currents, (b, e) output voltages of the system, and (c, f) their relationships,
corresponding to (left) the low gain antenna and (right) the high gain antenna. Adopted from Yang
et al. [2008, Figure 3].
mitted via ISOBE5600 fiber-optic link system which has a bandwidth of DC to 20 MHz. The ISOBE5600 system is available with individual, single channel transmitter units working with a receiver that supports up to four transmitters. Four transmitter units and one receiver have been used in the summer of 2009.

The close magnetic fields at 60 m from the channel are measured by a system which includes two rectangular loops perpendicular to each other. The system was developed in 2005, and different gain antennae were designed separately in order to obtain both small and large signals in 2006. The system was calibrated in a high-voltage laboratory by using a 120 kA pulse current generator, and quantitative results were obtained. The waveforms detected by the system are very similar to the source current (see Figure 1, adopted from Yang et al. [2008]). The experiment was repeated many times, and similar results were obtained. With considering the fitted value of $R^2$ in Figures 1c and 1f, it can be concluded that the developed system works stably and reliably. Since the summer of 2006, the system has been used in artificially triggering lightning experiment and it gave very good performance (see Table 1, and some results could also be seen in the work of Qie et al. [2009]). More detailed information of the magnetic field measuring system and its test results in high-voltage laboratory could be found in the work of Yang et al. [2008].

3. Data and Analysis

3.1. Statistical Distributions of Return Stroke Peak Currents

From SHATLE 2005 to 2009, 27 return stroke currents were directly measured at the channel base. As shown in Table 1, the 27 return stroke currents were included in seven triggered flashes. The flash 0804 contained four return strokes, but only one return stroke was recorded.

<table>
<thead>
<tr>
<th>Date</th>
<th>Flash Number</th>
<th>Time</th>
<th>Duration/ms</th>
<th>Technique</th>
<th>Currents</th>
<th>Magnetic Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 June 2005</td>
<td>0501</td>
<td>2229:25</td>
<td>837.6</td>
<td>classical</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td>0502</td>
<td>2233:30</td>
<td>732.0</td>
<td>classical</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>2 August 2005</td>
<td>0503</td>
<td>0004:02</td>
<td>1120.0</td>
<td>classical</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td>0504</td>
<td>0019:40</td>
<td>750.4</td>
<td>altitude</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td>0505</td>
<td>0024:12</td>
<td>518.0</td>
<td>altitude</td>
<td>×</td>
<td>×</td>
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<tr>
<td>5 July 2006</td>
<td>0600</td>
<td>2101:11</td>
<td>1900.0</td>
<td>classical</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 August 2006</td>
<td>0602</td>
<td>1941:49</td>
<td>584.0</td>
<td>classical</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>9 July 2007</td>
<td>0701</td>
<td>2308:29</td>
<td>990.0</td>
<td>classical</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>29 June 2008</td>
<td>0801</td>
<td>1459:47</td>
<td>1125.7</td>
<td>classical</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td>0802</td>
<td>1506:29</td>
<td>956.8</td>
<td>classical</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td>0803</td>
<td>1508:45</td>
<td>978.8</td>
<td>classical</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td>0804</td>
<td>1511:26</td>
<td>1362.7</td>
<td>altitude</td>
<td>*</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td>0805</td>
<td>1515:11</td>
<td>951.8</td>
<td>altitude</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>5 August 2009</td>
<td>0900</td>
<td>1435:52</td>
<td>428.6</td>
<td>classical</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td>0902</td>
<td>1439:16</td>
<td>622.2</td>
<td>classical</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>15 August 2009</td>
<td>0903</td>
<td>1358:46</td>
<td>145.5</td>
<td>classical</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

A checkmark indicates the data could be used, and a cross indicates that it could not. A dash symbol indicates that the triggered flash did not contain return strokes. The asterisk indicates flash 0804 contains four return strokes, but only one return stroke was recorded.

Figure 2. Typical current and magnetic field waveforms of the second return stroke in triggered flash 0602. (a) Channel base current and (b) magnetic field measured at 60 m from the channel.

Figure 3. Typical current and magnetic field waveforms of the sixth M component in triggered flash 0902. (a) Channel base current and (b) magnetic field measured at 60 m from the channel.
was located only 60 m away from the channel, the Ampere’s law of magnetostatics \( B = \mu_0 I / 2\pi r \) has been used. The consistency between the directly measured currents and estimated ones is considered as an important indicator of the good performance of the system.

Figure 2 shows the channel base current of the second return-stroke in triggered flash 0602, and the magnetic field at 60 m from the channel. The waveforms of the current and magnetic field were quite similar to each other and the estimated peak current 29.1 kA was in good agreement with the measured one 29.6 kA. Figure 3 shows the channel base current of the sixth M component in triggered flash 0902 and the magnetic field at 60 m from the channel. The waveforms of the current and magnetic field were almost the same. Relationship between the estimated peak currents and the directly measured ones was investigated, and it was found that the two were in good agreement in most of the cases, and the determination coefficient \( R^2 \) of the fitted line was about 0.83 (see Figure 4). It is not easy to get current and magnetic field data simultaneously. Some return strokes struck the lightning rod but their magnetic fields saturated, some have good magnetic field data but did not strike the lightning rod, which lead to a small sample size of synchronous current and magnetic field data in Figure 4, even if the M components were included.

The statistical distributions of current waveforms discussed here include parameters of return stroke peak current, half-peak width, 10–90% risetime \( (T_{-10}) \), and charge transfer within 1 ms, all of which have the same definitions as Schoene’s [e.g., Schoene et al. 2009]. The total stroke duration, interstroke intervals, front steepness \( S_{10} \) and \( S_{30} \), 30–90% risetime, and stroke action integral have the same meanings as Fisher’s [e.g., Fisher et al. 1993]. The same definitions adopted as other authors’ will make comparative

Figure 4. Relationships between the directly measured currents and the estimated ones from the magnetic fields at 60 m from the channel. The “est” and “dir” in the equation are abbreviations of “estimated currents” and “directly measured ones.”

Figure 5. Distributions of return stroke parameters. (a) Return stroke peak currents; (b) total stroke duration; (c) return stroke half-peak widths; (d) return stroke charge transfers within 1 ms; (e) interstroke intervals; (f) return stroke action integral within 1 ms; (g) 10–90% risetime, \( T_{-10} \); (h) front steepness, \( S_{10} \); (i) \( T_{-30} \); and (j) front steepness, \( S_{30} \). The sample size 27 indicates that only directly measured return stroke currents have been used. The sample size 48 and 38 indicates that both of the directly measured currents and estimated currents from magnetic fields have been used.
Table 2. Comparison of Current Waveform Parameter Statistics Obtained From the 2005 Through 2009 SHATLE Experiment With Results From Other Studies

<table>
<thead>
<tr>
<th>Experiment Site</th>
<th>Sample Size</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Arithmetic Mean</th>
<th>Standard Deviation</th>
<th>Geometric Mean</th>
<th>Standard Deviation (log10 (+))</th>
<th>Selected References</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHATLE 2005–2009</td>
<td>48</td>
<td>5.8</td>
<td>45.7</td>
<td>16.3</td>
<td>9.8</td>
<td>14.1</td>
<td>0.22</td>
<td>This study</td>
</tr>
<tr>
<td>SHATLE 2005–2008</td>
<td>21</td>
<td>6.6</td>
<td>41.6</td>
<td>17.2</td>
<td>10.5</td>
<td>14.6</td>
<td>0.24</td>
<td>[Zhao et al., 2009]</td>
</tr>
<tr>
<td>Camp Blanding, Florida, 1999–2004</td>
<td>165</td>
<td>2.8</td>
<td>42.3</td>
<td>13.9</td>
<td>6.9</td>
<td>12.2</td>
<td>0.22</td>
<td>[Schoene et al., 2004]</td>
</tr>
<tr>
<td>Camp Blanding, Florida, 1999–2000</td>
<td>64</td>
<td>5.0</td>
<td>36.8</td>
<td>16.2</td>
<td>7.6</td>
<td>14.5</td>
<td>0.21</td>
<td>[Schoene et al., 2003a]</td>
</tr>
<tr>
<td>Camp Blanding, Florida, 1998</td>
<td>25</td>
<td>5.9</td>
<td>33.2</td>
<td>14.8</td>
<td>7.0</td>
<td>13.5</td>
<td>0.19</td>
<td>[Uman et al., 2000]</td>
</tr>
<tr>
<td>Camp Blanding, Florida, 1997</td>
<td>11</td>
<td>5.3</td>
<td>22.6</td>
<td>12.8</td>
<td>5.6</td>
<td>11.7</td>
<td>0.20</td>
<td>[Crawford, 1998]</td>
</tr>
<tr>
<td>Camp Blanding, Florida, 1993</td>
<td>37</td>
<td>5.3</td>
<td>44.4</td>
<td>15.1</td>
<td>-</td>
<td>13.3</td>
<td>0.23</td>
<td>[Rakov et al., 1998]</td>
</tr>
<tr>
<td>KSC, Florida 1990, Alabama 1991</td>
<td>45</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12.0</td>
<td>[Fisher et al., 1993]</td>
</tr>
<tr>
<td>France, Saint-Privat d’Allier 1986,1990–1991</td>
<td>54</td>
<td>4.5</td>
<td>49.9</td>
<td>11.0</td>
<td>5.6</td>
<td>-</td>
<td>-</td>
<td>[Depasse, 1994]</td>
</tr>
<tr>
<td>KSC, Florida 1985–1991</td>
<td>305</td>
<td>2.5</td>
<td>60.0</td>
<td>14.3</td>
<td>9.0</td>
<td>-</td>
<td>-</td>
<td>[Depasse, 1994]</td>
</tr>
</tbody>
</table>

Current 10–90% Risetime (μs)

<table>
<thead>
<tr>
<th>Experiment Site</th>
<th>Sample Size</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Arithmetic Mean</th>
<th>Standard Deviation</th>
<th>Geometric Mean</th>
<th>Standard Deviation (log10 (+))</th>
<th>Selected References</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHATLE 2005–2009</td>
<td>27</td>
<td>0.4</td>
<td>8.4</td>
<td>2.7</td>
<td>2.1</td>
<td>2.0</td>
<td>0.34</td>
<td>This study</td>
</tr>
<tr>
<td>SHATLE 2005–2008</td>
<td>21</td>
<td>0.4</td>
<td>8.4</td>
<td>3</td>
<td>2.2</td>
<td>2.3</td>
<td>0.33</td>
<td>[Zhao et al., 2009]</td>
</tr>
<tr>
<td>Camp Blanding, Florida, 1999–2004</td>
<td>81</td>
<td>0.2</td>
<td>5.7</td>
<td>1.2</td>
<td>0.8</td>
<td>0.9</td>
<td>0.32</td>
<td>[Schoene et al., 2009]</td>
</tr>
<tr>
<td>KSC, Florida 1990, Alabama 1991</td>
<td>43</td>
<td>-</td>
<td>2.9</td>
<td>-</td>
<td>0.37</td>
<td>0.29</td>
<td>[Fisher et al., 1993]</td>
<td></td>
</tr>
<tr>
<td>Camp Blanding, Florida, 1997</td>
<td>11</td>
<td>0.3</td>
<td>4.0</td>
<td>0.9</td>
<td>1.2</td>
<td>0.6</td>
<td>0.39</td>
<td>[Crawford, 1998]</td>
</tr>
</tbody>
</table>

Current Half-Peak Width (μs)

Return-Stroke Charge Transfer Within 1 ms (C)

Figures 6 and 7 illustrate typical triggered lightning return-stroke magnetic field waveform measured at a distance of 60 m from the channel (the second stroke in triggered flash 0602). The following parameters are illustrated: (a) magnetic field peak; peak; (b) 10–90% risetime, T-10; (c) 30–90% risetime, T-30; and (d) half peak width, T-HPW.

Study more reasonable. It is worth noting that only return stroke peak current and interstroke intervals contain both directly measured currents and estimated ones from magnetic fields, other parameters were obtained only from the directly measured current waveforms. The statistical histogram of these parameters have been shown in Figure 5 and compared with other studies in Table 2. Some results from directly measured current in SHATLE 2005–2008 have been discussed by Zhao et al. [2009]. It is worth noting that the interstroke intervals were obtained from both the magnetic field and current data, while other parameters (except peak current and interstroke interval) were obtained only from directly measured currents. Consequently, the sample sizes in different plots in Figure 5 are not the same.

The results showed that the return stroke peak current varied from a minimum of 5.8 kA to a maximum of 45.7 kA, which is a little larger than that of the results (a maximum of 42.3 kA and a minimum of 2.8 kA) obtained by Schoene et al. [2009]. The geometric mean (GM) of peak current was 14.1 kA, which was a little larger than most of the results.
obtained in Florida, excepting the results (14.5 kA) obtained in 1999–2000 Camp Blanding, Florida (see Table 2). Up to now, the smallest directly measured peak current was 2.5 kA and largest close to 60 kA obtained in Florida [e.g., Depasse, 1994; V. A. Rakov et al., Review of triggered lightning experiments at the ICLRT at Camp Blanding, Florida, paper presented at Power Tech Conference, IEEE, Bologna, Italy, 2003]. Most of the results reported by other authors seemed to fall in this range.

[11] Statistical histogram shown in Figure 5 indicated that the peak value of the 10–90% risetime in current waveform was between 1 and 2 μs, consistent with most of the results found in the literature [e.g., Depasse, 1994; Schoene et al., 2009]. By comparing with other studies, the 10–90% risetime in this study covered a wide range from 0.4 to 8.4 μs. The arithmetic mean was about 2.7 μs, which was two times larger than that reported by Schoene et al. [2009]. It is worth noting that most of the directly measured channel base currents were measured properly by the Rogowski coils due to its comparatively high bandwidth. On the other hand, the narrow bandwidth of the instrument and its low upper cutoff frequency may be also responsible for the comparatively large 10–90% risetimes. In addition, the narrow bandwidth of the instrument and its low upper cutoff frequency may be also responsible for the comparatively large 10–90% risetimes. The readers should keep in mind of these factors when considering the risetime values in the conjunction points. Therefore we speculate that reflections might be the main reason for the large 10–90% risetimes. In our case, the lightning rod is not a complete one but composes of several parts which may lead to more reflections in the conjunction points.

Table 3. Values of Parameters in Heidler Function

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>29.6</td>
</tr>
<tr>
<td>η</td>
<td>0.6</td>
</tr>
<tr>
<td>τ1(μs)</td>
<td>0.9</td>
</tr>
<tr>
<td>τ2(μs)</td>
<td>3.6</td>
</tr>
<tr>
<td>n</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 8. (a) Simulated and directly measured current of the second return stroke in flash 0602 and (b) calculated and measured magnetic fields at 60 m from the channel.
close to the 142 half-peak widths (arithmetic mean: 23 µs; standard deviation: 17 µs) reported by Schoene et al., [2009] but smaller than that of the results obtained by Crawford [1998]. Fisher et al. [1993] points out that insufficient low frequency response of the measurement will result in an underestimation of the half-peak width. Because the half-peak width is very sensitive to errors in the measurement of peak current. Low frequency errors due to an insufficient low-frequency response of the measurement system will affect the tail of the lightning current waveform in such a way that the current decays faster [e.g., Schoene et al., 2009]. This will result in an underestimation of the half-peak width. According to this theory, the smaller value of the half-peak width in this study may be due to the higher low cutoff frequency (in our case it is 300 Hz) of the measurement system. An insufficient high-frequency response typically results in underestimated current peak, which results in overestimation of the half-peak width since the width of the waveform at half-peak value is determined closer to the bottom, where the waveform is wider [Schoene et al., 2009]. Inspection of current waveforms indicates that a reduction in peak current by 20% will increase the half-peak width by about 40% [Fisher et al., 1993]. In present paper, the high cutoff frequency of the Rogowski coil is 1.5 MHz, and the shunt 3.2 MHz, both of which are much lower than that of the system used by [Schoene et al. 2009] (from DC to at least 10 MHz). From the above discussion, it is unknown whether our results are underestimated or overestimated. The limited number of available data may also affect the results. Therefore half-peak width statistics in this paper and in the literature should be viewed critically because of these potential problems.

The charge transferred was obtained by numerically integrating the measured return stroke current over time interval of 1 ms. The GM of charge transferred was about 1.1 C, with an logarithmic standard deviation of 0.22, which are close to results of the 151 charge transfers (GM: 1.0 C, logarithmic standard deviation: 0.35) obtained by Schoene et al. [2009]. The charge transferred varied from 0.3 C to 4.2 C with an arithmetic mean of 1.2 C. In order to compare with results from other authors, the integral time was limited to 1 ms, but about 81.5% of return stroke durations were larger than this value with the maximum of 17.8 ms. If the return stroke duration was chosen as the integral time, the component of continuous current will be definitely included and the charge transferred will be much larger. Because the return stroke duration defined here is the time interval from the onset of a return stroke current to the time at which the measured current becomes indistinguishable from the noise level. The results

![Figure 9](image1.png)

**Figure 9.** Effects of return stroke speed on magnetic fields at 60 m from the channel.

![Figure 10](image2.png)

**Figure 10.** Contributions of induction and radiation field components to total magnetic fields at 60 m from the lightning channel for different return stroke speeds.

![Figure 11](image3.png)

**Figure 11.** Time-variation contributions of induction and radiation field component to the total magnetic fields at 60 m from the lightning channel for different return stroke speeds.
show that for stroke duration much longer than 1 ms, the charge transferred during this duration will be several times larger than that in 1 ms, indicating the continuous current plays a very important role in charge transfer process. Relationships between discharge parameters show there were no correlations between peak currents, $T_{10}$, $T_{30}$, and half-peak widths. Recently, Schoene et al. [2010] analyzed correlations between return stroke peak currents and charge transferred, showing that the determination coefficient ($R^2$) decreases with increasing duration of the charge transfer after the return stroke onset and that the correlation is the strongest for charge transfers up to a few tens of microseconds. When the duration is limited to 10 microseconds, Schoene obtained the $R^2$ was 0.96. In our case the $R^2$ was not so high, which may be due to the comparatively small sample size.

3.2. Statistical Distributions of Close Magnetic Fields

Characteristics of channel base currents have been analyzed in above paragraphs in detail. In this section, statistical distributions which characterize the close electromagnetic environment of triggered flashes will be investigated based on 32 return strokes (other return strokes saturated and were not suitable for analysis). The parameters analyzed include magnetic field peak, 10–90% risetime ($T_{10}$), 30–90% risetime ($T_{30}$), and half-peak width, and their definitions are shown in Figure 6. The statistical distributions shown in Figure 7 indicated that the magnetic field peak varied from a minimum of 18 $\mu$T to a maximum of 148 $\mu$T with an arithmetic mean of 62 $\mu$T and a GM of 52 $\mu$T (See Table 3). It is worth noting that the peak of 148 $\mu$T are produced by an altitude triggered flash, and its estimated peak current was about 44.4 kA, similar to the peak current of 44 kA of an altitude triggered flash obtained by Saba et al. [2005] in Brazil. The magnetic field peak value was between 30 and 50 $\mu$T.

[15] The peak value of the 10–90% magnetic field risetime was 1–2 $\mu$s with a range from 0.4 to 8.4 $\mu$s. The geometric and arithmetic means of risetimes were 2.5 and 3.2 $\mu$s, respectively, which were about four times larger than that at 5.5 and 10.3 m reported by Crawford [1998]. The 30–90% risetime varied from 0.3 to 8.0 $\mu$s, with arithmetic mean of 2.7 $\mu$s and a GM of 2 $\mu$s, which were about seven or six times larger than the corresponding values at 15 and 30 m obtained by Schoene et al. [2003a]. The arithmetic mean of magnetic field half-peak width ($T_{HPW}$) was about 12.7 $\mu$s. Schoene et al. [2003a] found $T_{HPW}$ arithmetic means of 17.4 $\mu$s and 14.6 $\mu$s at 15 and 30 m, respectively. Schoene et al. [2003a]
obtained a narrower magnetic field T‐HPW compared with results reported by Crawford [1998], and he pointed out that although the measurements were made at different distances the lower grounding resistance may be responsible for the comparatively narrower T‐HPW. In our experiment, although no metal grids were buried as was done in Florida, the grounding resistance was also very low (2.3 \( \Omega \)) because of the saline‐alkali soil at the experiment site. So according to Schoene’s view [e.g., Schoene et al., 2003a], the narrower T‐HPW in present study may to some extent also result from the low grounding resistance.

4. Numerical Study of Close Magnetic Fields

[16] Statistical distributions of channel base currents and close magnetic fields have been analyzed and compared with other studies in detail in above paragraphs. Relationships between channel currents and close electromagnetic fields have been expressed analytically by different authors [e.g., Master and Uman, 1983; Thottappillil and Uman, 1993; Uman et al., 1975]. But how do different parameters, such as current risetime, return stroke speed, distance, and peak current, etc, affect close magnetic fields? In this section, effects of these factors on close magnetic fields will be examined by using numerical method. Thottappillil et al. [1997] showed that the measured close electric fields were consistent with predicted results by using Bruce‐Golde (BG), Modified Transmission Line model with Linear current decay with height (MTLL), Traveling Current Source (TCS), and Dien‐dorfer–Uman (DU) models. Thottappillil and Uman [1993] found that the transmission line model is not adequate for modeling the fields at later times after the peak. Results reported by Schoene et al. [2003b] indicated that all modeled electric fields by using transmission line model (TLM) are larger than the measured fields, and the predicted electric and magnetic fields with Traveling Current Source Model (TCSM) have a narrow spike in the rising portion of the waveforms which is not present in the measured fields. On the basis of the entirety of the testing results and mathematical simplicity, the modified transmission line model with linear current decay with height (MTLL) [e.g., Rakov and Dulzon, 1987; Thottappillil et al., 1997] is adopted in this paper.

\[
i(\tau, t) = u(t - \frac{\tau}{v}(1 - \frac{\tau}{H}))i_0(0, t - \frac{\tau}{v})
\]

where \( \tau \) is the current height in a straight and vertical channel and \( \tau = 0 \) at the channel origin, \( H \) is the length of the channel, \( u \) is the Heaviside function equal to unity for \( t \geq \frac{\tau}{v} \) and zero otherwise, \( v \) is the return stroke speed, and \( i_0 \) is the channel base current and is approximated by the Heidler function (F. Heidler, Traveling current source model of LEMP calculation, paper presented at 6th International Symposium on Electromagnetic Compatibility, Swiss Fed. Inst. of Technol., Zurich, 1985) and their parameter values are shown in Table 4.

\[
i_0(t) = \frac{C_n}{\eta} \left( \frac{t}{\tau} \right)^n e^{-t/\tau}
\]

The expressions of electromagnetic fields produced by lightning are commonly found in the literature [e.g., Master and Uman, 1983; Uman et al., 1975] and are used in this paper. The expression of the magnetic field is reproduced below for convenience.

\[
B(r, t) = \frac{u_0}{2\pi} \left[ \int_0^H \left( \frac{r}{R^2} \frac{\partial i(t - R/c)}{\partial t} \right) dl + \int_0^H \left( \frac{r}{cR^2} \frac{\partial i(t - R/c)}{\partial t} \right) dl \right]
\]
where \( \mu_0 \) is the permeability of free space and \( c \) is the speed of light. \( R \) is the distance between the current element and the observation point \( p \) and \( r \) is a vector pointing from the origin to field point \( P \). Figure 8a shows the directly measured current and the simulated one by using this method, suggesting the two of them were consistent. Figure 8b shows the calculated and measured magnetic fields at 60 m from the channel. Although the risetime of the measured and simulated waveforms were different, the peak values of the two were in good agreement, indicating the method used is reasonable. Effects of different factors on magnetic fields will be investigated in the following paragraphs. It should be noted that some of these quantities are model-dependent.

[17] Figure 9 shows effect of return stroke speed on magnetic fields at 60 m from the channel. The results indicate that for larger speeds, the magnetic field peak values are larger and half-peak widths and risetimes are smaller, consistent with magnetic field derivatives obtained by Schoene [2002] with Mathcad method. The magnetic field peaks and risetimes for different return stroke speeds are easy to compare, but the half peak widths are not. Therefore numerical values of half-peak widths in total magnetic field are given here and they are 6.5, 6, and 5.7 \( \mu s \) for \( v = c/3 \), \( v = c/2 \), and \( v = c \), respectively. Figure 10 shows that the induction component dominates at 60 m for different return stroke speeds (this is in the case when the total magnetic field reaches the peak). The contribution of induction and radiation components to total magnetic field peaks do not depend much on assumed speed. But if we look at the time-variation contribution shown in Figure 11, it can be found that the contribution of different components to the total magnetic field is variable. The induction component dominates at the time when the magnetic field reaches its peak but the radiation component dominates for the first 1 \( \mu s \) or so. At the intersection point of the two curves the contributions of the two components are equal. After that the induction component increases and radiation component decreases until the induction field dominates.

[19] Figure 12 shows different magnetic field components at different distances from the lightning channel when the return stroke speed equals to \( 1.5 \times 10^8 \) m/s. With calculated magnetic field peaks at 10 and 100 m, the results indicated a distance dependence of \( r^{-0.97} \), which is a little different from results (\( r^{-0.93} \)) at 15 and 30 m obtained by Schoene et al. [2003a] but which is consistent with results reported by Crawford [1998]. These results suggest a distance dependence close to \( r^{-1} \) at close observation site, which is in agreement with theoretical predictions that the induction component dominates (see Figure 13) when the channel length is much larger than the observation distance, and the induction component is proportional to \( r^{-1} \). At distances of 1000 m or larger, the radiation component dominates and the distance dependence at 100 and 1000 m was about \( r^{-0.38} \), quite different from \( r^{-1} \). At different distances the contribution of different components varies drastically with the induction field dominates within 100 m and radiation field dominates beyond 1000 m. The time variation contribution of induction and radiation components at different distances shown in Figure 14 is quite different from that shown in Figure 11 for different return stroke speeds. The results indicated that for smaller distances, the curves of time variation contribution of induction and radiation components go up and down sharply than that for larger distances. The time at which the component contributions are equal comes later at larger distances. In addition, there seems to be a turning point between 160 and

\[ \text{Figure 17. Time-variation contributions of induction and radiation field component to the total magnetic fields for different risetime at 60 m from the lightning channel for } v = 1.5 \times 10^8 \text{ m/s.} \]

\[ \text{Figure 18. Model-predicted magnetic fields for different return stroke peak currents at 60 m from the lightning channel by using MTLL for } v = 1.5 \times 10^8 \text{ m/s.} \]

\[ \text{Figure 19. Time-variation contributions of induction and radiation field component to the total magnetic fields for different return stroke peak currents at 60 m from the lightning channel for } v = 1.5 \times 10^8 \text{ m/s.} \]
200 μs in Figure 14c, after the point the contribution of induction and radiation component approaches 1 and zero, respectively, which was not observed in curves in Figures 14a and 14b for distances at 10 and 100 m. The cause of this phenomenon is not yet known.

Figure 15 shows that for smaller current risetime the magnetic field half-peak widths and risetimes are smaller but magnetic field peak values are larger. The half-peak widths of total magnetic fields are 3, 5.5 and 7.3 μs for current risetimes 0.2, 1.2 and 2.2 μs, respectively. With increasing current risetime, the contribution of induction component becomes a slightly larger as shown in Figure 16, but this increasing tendency becomes inconspicuous for larger current risetime. Considering the time-variation contribution of the induction and radiation component shown in Figure 17, the time at which the equal contribution of the two components occurs later with increasing current risetime, but this tendency also becomes inconspicuous for larger current risetime (this could be seen clearly in Figures 17b and 17c). Figures 18–20 show effect of return stroke peak current on the magnetic field induction and radiation components at 60 m from the lightning channel. With increasing the peak currents the magnetic field peak increases linearly. The numerical values of half-peak widths in total magnetic field are 6, 5.5 and 5.4 μs for i = 10 kA, i = 20 kA, and i = 30 kA, respectively. As shown in Figures 19 and 20, the contributions of different components do not depend on the peak current.

5. Conclusions

The magnetic field measuring system gave good performance in SHATLE experiment since the summer of 2006. The estimated peak currents from the magnetic fields and the directly measured ones were in good agreement (the coefficient R^2 = 0.83). The newly designed rockets, new shunt for current measurement and new optical links performed well during the experiment. Statistical results of current waveforms showed that the peak currents varied from 5.8 kA to 45.7 kA with a GM of 14.1 kA, generally consistent with those reported from other triggered-lightning studies. The GM of 10–90% current risetime was 2.0 μs and the peak value of the 10–90% risetime was between 1 and 2 μs, which was consistent with most of the results in the literature [e.g., Depasse, 1994; Schoene et al., 2009]. The arithmetic mean of half-peak width was 27.0 μs with standard deviation of 13.8 μs, both of which were close to results reported by Schoene et al. [2009] (arithmetic mean: 23 μs; standard deviation: 17 μs). The GM of charge transferred within 1 ms was 1.1 C (logarithmic standard deviation: 0.22), also consistent with other studies.

Statistical distributions of close magnetic field show that the GM of magnetic field peak at 60 m was 52 μT with a range from 18 to 148 μT. The magnetic field peak value was between 30 and 50 μT. The peak value of the 10–90% risetime was 1–2 μs with a minimum of 0.4 μs and a maximum of 8.4 μs. The geometric and arithmetic mean values of the risetime was 2.5 and 3.2 μs, respectively, which were about four times larger than the values at 5.5 and 10.3 m reported by Crawford [1998]. The arithmetic and geometric mean values of 30–90% risetime was about 2.7 μs and 2 μs, respectively, which were about seven or six times larger than the corresponding values at 15 and 30 m obtained by Schoene et al. [2003a]. The arithmetic mean of half-peak width was 12.7 μs.

Effects of return stroke speed, distance, current risetime, and peak value on magnetic field induction and radiation component have been investigated. The results show that for larger speeds, the magnetic field peak values are larger, but half-peak widths and risetimes are smaller. The contribution of induction and radiation components to total magnetic field peaks depend slightly on assumed return stroke speed and current risetime, and in general, do not depend on peak current, but depend much on the distance. Effects of distance on the time-variation contribution of induction and radiation components are quite different from that of return stroke speed and current risetime. With increasing the distance or current risetime, the magnetic field peak value decrease but the risetime and half-peak width increase.

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