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X-Ray Emissions from First and Subsequent Leaders in Natural Cloud-to-Ground Lightning

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ABSTRACT: X-ray emissions associated with both first and subsequent strokes in natural cloud-to-ground lightning are examined. A total of 84 negative strokes (23 first and 61 subsequent) within 2 km of the Lightning Observatory in Gainesville in 29 flashes were recorded. The occurrence of detectable X-rays was 78% and 33% for first and subsequent strokes, respectively. There is a significant difference between estimated X-ray source heights for first and subsequent strokes. For first leaders, the median source height was 64 m (with a maximum of 1.6 km), whereas for subsequent leaders the median source height was 610 m (with a maximum of 6.7 km). Not all leaders within a flash produced detectable X-rays. For the same leader near ground, some steps were accompanied by detectable X-ray emissions, while others were not.

INTRODUCTION

Lightning emits electromagnetic energy at frequencies from less than 1 Hz to about 10^{20} Hz [Rakov and Uman, 2003]. Moore et al. [2001] were the first to detect X-ray emissions associated with natural lightning in New Mexico and Dwyer et al. [2004], working at Camp Blanding (CB), Florida, were the first to detect X-ray emissions from rocket-triggered lightning.

X-ray emissions associated with both first and subsequent strokes in natural lightning were presented by Mallick et al. [2012]. They reported X-ray emissions associated with 23 (8 first and 15 subsequent) strokes in 12 negative downward cloud-to-ground (CG) flashes occurring within 2 km of the Lightning Observatory in Gainesville (LOG), Florida, in 2011. The occurrence of detectable X-rays was 88% and 47% for the first and subsequent strokes, respectively. Not all leaders within a flash produced detectable X-rays. The occurrence of X-rays tended to increase with increasing the return-stroke peak current and decreasing distance from the lightning channel, as expected. The energy of some photons was in the MeV range (in one case possibly in excess of 5 MeV). Some subsequent-stroke (dart and dart-stepped) leaders were more prolific producers of detectable X-rays than their corresponding first-stroke (stepped) leaders. For the same leader near ground, some steps were accompanied by detectable X-ray emissions, while others were not.

In this paper, we will extend the study of Mallick et al. [2012] to additionally include 61 (15 first and 46 subsequent) strokes in 17 flashes, occurring within 2 km of LOG in 2012, all of which produced

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detectable X-ray emissions.

METHODOLOGY AND INSTRUMENTATION

Examined here are X-ray emissions associated with natural lightning recorded at LOG on August 20, September 9, and December 10, 2012, in addition to those recorded on July 31, 2011, and reported by Mallick et al. [2012]. X-rays were measured by a NaI(Tl) scintillator coupled with a photomultiplier tube (PMT). Wideband electric field (E) and electric field derivative (dE/dt) records, were also acquired at LOG, using circular flat-plate antennas. The X-ray detector and flat-plate antennas were installed on the roof of a five-storey building. Fiber optic links were used to transmit signals from the X-ray detector and field measuring systems to a digitizing oscilloscope. More detailed information on LOG can be found in Rakov et al. [2014] and Mallick et al. [2012].

On July 31, 2011, the digitizing oscilloscope had 8-bit resolution and 240 ms record length. On August 20 and September 9, 2012, the digitizing oscilloscope had 8-bit resolution and 500 ms record length. On December 10, 2012, the digitizing oscilloscope had 12-bit resolution and 1 s record length. The oscilloscope operated at a sampling rate of 100 MHz for all the days on which X-rays were observed. The oscilloscope recorded E, dE/dt, and X-rays. In 2012, dE/dt signals were recorded in two channels with different gains. The low-gain channel was used to determine the onset of return strokes and the high-gain channel was used for recording leader-step pulses.

The X-ray detector was calibrated with a Cs-137 radioactive source producing 662 keV photons (see Mallick et al. [2012]). The lowest measurable signal amplitudes corresponded to 128 keV on July 31, 2011, on August 20, 2012, and on September 9, 2012, and it was 75 keV on December 10, 2012.

A total of 84 negative strokes (23 first and 61 subsequent) within 2 km of LOG in 29 flashes were recorded. Out of the 84 strokes, 27 produced X-ray bursts, 11 produced single X-ray pulses, and 46 did not produce detectable X-ray emissions during 2 ms prior to (or during the leader/return stroke process when it was shorter than 2 ms) and 10 µs after the onset of return stroke. The 38 strokes which produced detectable X-rays occurred in 20 flashes. Of these 38, 18 were first strokes and 20 were subsequent strokes. The X-ray burst is defined as a sequence of two or more X-ray pulses (not necessarily a single photon per pulse, see Mallick et al. [2012]). The occurrence of detectable X-rays was 78% and 33% for first and subsequent strokes, respectively. Table 1 gives a summary of the flashes/strokes examined in the present study.

Distances to lightning channels and peak currents were estimated by the U.S. National Lightning Detection Network (NLDN). Median location errors (assumed to be equal to the semimajor axis lengths of 50% location error ellipses) were 0.2 km for 76 (90%) out of 84 strokes examined here. In this paper, all NLDN-reported distances expressed in meters were rounded off to two significant digits. The median absolute error in peak current estimates for subsequent strokes is less than 15% (based on comparison with directly measured currents for triggered-lightning strokes; Mallick et al. [2014]) and is presently unknown for first strokes. NLDN data were also used to determine the total number of strokes in a flash (in some cases our record length did not allow us to capture all the strokes).

Table 1 Summary of Flashes/Strokes with X-Rays Recorded at LOG in 2011–2012

Date	Number of Flashes	Number of Strokes Within 2 km of LOG[a]	Number of Strokes That Produced Detectable X-Rays[a]		
			Bursts	Single	All
July 31, 2011[b]	12	23 (8 + 15)	11 (5 + 6)	3 (2 + 1)	14 (7 + 7)
August 20, 2012	6	22 (6 + 16)	8 (3 + 5)	1 (0 + 1)	9 (3 + 6)
September 9, 2012	7	29 (6 + 23)	5 (4 + 1)	3 (1 + 2)	8 (5 + 3)
December 10, 2012	4	10 (3 + 7)	3 (2 + 1)	4 (1 + 3)	7 (3 + 4)
Total	29	84 (23 + 61)	27 (14 + 13)	11 (4 + 7)	38 (18 + 20)

[a]The first and second numbers in the parentheses correspond to first and subsequent strokes, respectively.

[b]Previously reported by Mallick et al. [2012].

RESULTS AND DISCUSSION

Figure 1a shows E, dE/dt, and X-ray records for flash 617 recorded on August 20, 2012 and Figure 1b shows those for stroke 3 of this flash. Strokes 1, 2, 3, and 6 of flash 671 produced X-ray bursts, while strokes 4 and 5 did not produce detectable X-rays.

Tables 2 and 3 summarize occurrence of X-rays as a function of return stroke peak current and distance from the lightning channel, respectively. As expected, the occurrence of detectable X-rays tends to increase with increasing return-stroke peak current and decreasing distance from the lightning channel.

Figure 2 shows the occurrence of X-rays as a function of leader duration. Leader durations were estimated from our dE/dt records. From Figure 2, one can see that there are two groups of leaders. Those shorter than 8 ms are likely to be relatively fast dart or dart-stepped leaders, developing in previously formed channels, while those longer than 8 ms are slower stepped leaders, propagating through the virgin air.

The time intervals, Δt, between the X-ray pulse and the return-stroke onset were used for estimating X-ray source heights, $h = v \times \Delta t$ (where v is the average leader speed estimated from the leader duration measured in dE/dt records and assumed total channel length of 7.5 km [Rakov and Uman, 2003]). We also estimated inclined distances, $R = (r^2 + h^2)^{1/2}$ (where r is the NLDN-reported horizontal distance to the lightning channel) for all discernible pulses in our X-ray records. It was assumed, as a first approximation, that the lightning channel was vertical. Histograms of X-ray source heights and inclined distances are shown in Figures 3a and 3b, respectively. As reported by Mallick et al. [2012], there is a significant difference between estimated X-ray source heights for first and subsequent strokes. For first leaders, the median source height was 64 m (with a maximum of 1.6 km), whereas for subsequent leaders the median source height was 610 m (with a maximum of 6.7 km).

Figure 4 shows histogram of intervals between all discernible X-ray pulses for first and subsequent leaders. The interpulse intervals peak between 10 and 100 µs for first strokes and 1 and 10 µs for subsequent strokes. These correspond to typical inter-step time intervals for stepped and dart-stepped leaders [Rakov and Uman, 2003]. Sub-microsecond interpulse intervals mostly correspond to multiple photons contributing to an X-ray pulse (produced during a single leader step), and intervals greater than 100 μs are likely to be associated with the fact that not all leader steps produce detectable X-rays.

Figures 5a and 5b show scatter plots of the number of discernable X-ray pulses versus return-stroke peak current and versus distance to the lightning channel, respectively. Figures 6a and 6b show scatter plots of the maximum deposited X-ray energy per pulse (not necessarily for a single photon) versus return-stroke peak current and versus distance to the lightning channel, respectively. Figures 7a and 7b show scatter plots of the total deposited X-ray energy (sum of energies of all pulses) versus return-stroke peak current and versus distance to the lightning channel, respectively.

It is generally expected that first-stroke (stepped) leaders produce more X-rays than subsequent-stroke (dart or dart-stepped) leaders. Mallick et al. [2012] were the first to report that subsequent leaders can be more prolific producers of X-rays than the corresponding first ones. In this study, we found that in 3 out of 11 flashes with X-rays recorded from both first and subsequent strokes, one or more subsequent strokes were more prolific producers of X-rays than the first stroke, and in 2 flashes the first stroke produced more X-rays than any of the subsequent strokes did.

Mallick et al. [2012] reported that not all leader steps were associated with X-ray emissions. In this study, we found that at least one-half of the leader steps observed in E or dE/dt records did not have associated X-ray pulses. Detailed analysis of the occurrence of detectable X-ray emissions associated with individual steps is in progress.

CONCLUSIONS

X-ray emissions associated with both first and subsequent strokes in natural cloud-to-ground lightning were examined. A total of 84 negative strokes (23 first and 61 subsequent) within 2 km of the Lightning Observatory in Gainesville in 29 flashes were recorded. The occurrence of detectable X-rays was 78% and 33% for first and subsequent strokes, respectively. There is a significant difference between estimated X-ray source heights for first and subsequent strokes. For first leaders, the median source height was 64 m (with a maximum of 1.6 km), whereas for subsequent leaders the median source height was 610 m (with a maximum of 6.7 km). Not all leaders within a flash produced detectable X-rays. For the same leader near ground, some steps were accompanied by detectable X-ray emissions, while others were not.

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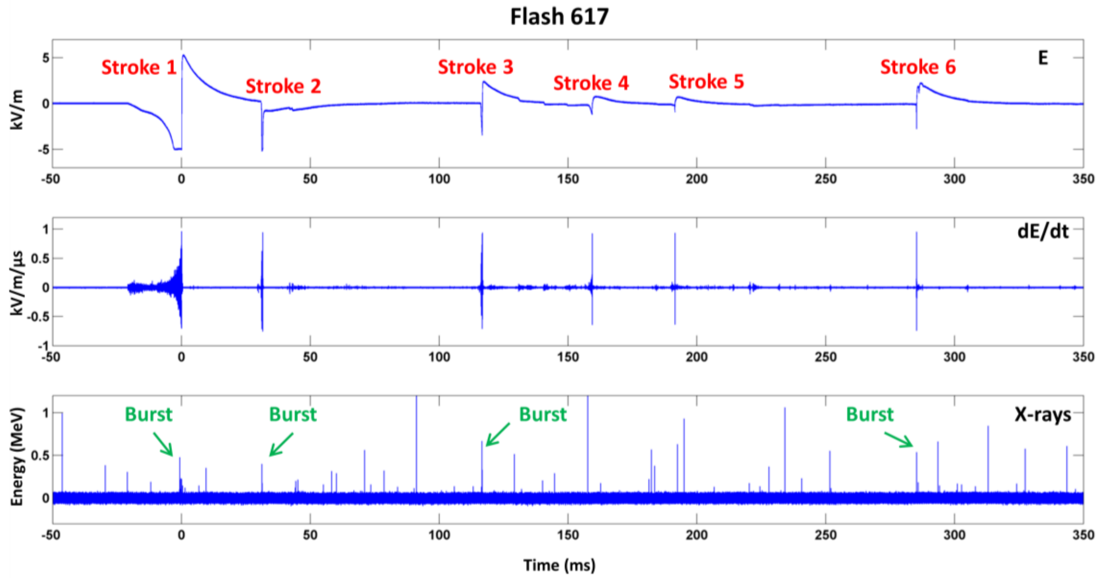
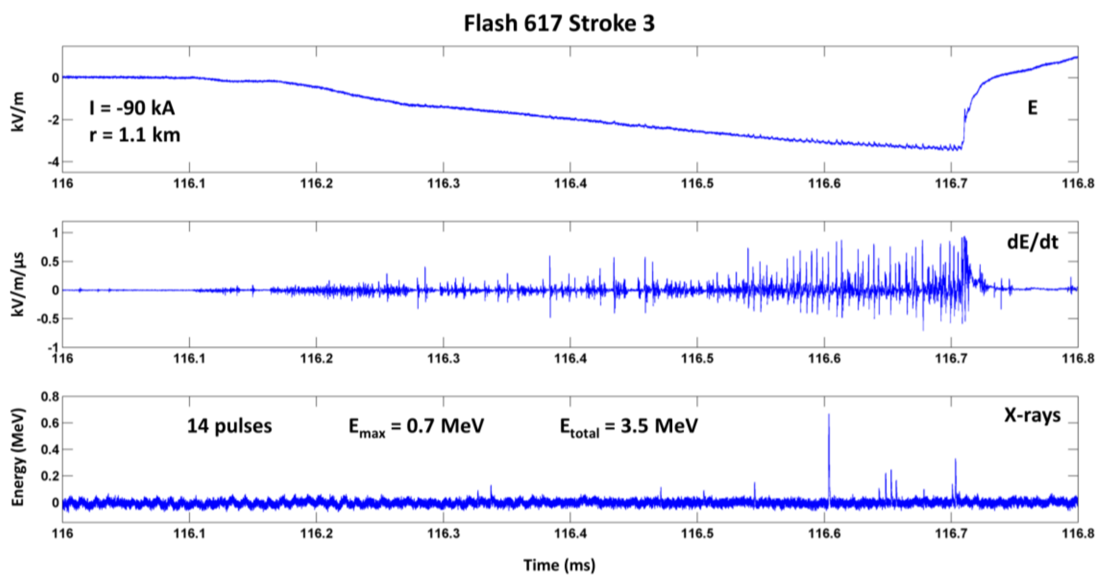


(a)



(b)

Figure 1. Electric field (E), dE/dt, and X-ray records for (a) flash 617 recorded on August 20, 2012 and (b) stroke 3 of flash 617. According to the NLDN, the flash consisted of 9 strokes. Only strokes 1 to 6 were recorded at LOG (500-ms record length). Strokes 1, 2, 3, and 6 produced X-ray bursts, while strokes 4 and 5 did not produce detectable X-rays. NLDN-reported peak current for stroke 3 was 90 kA, the largest among the six strokes recorded at LOG. The total number of discernible X-ray pulses (not necessarily single photons) was 14. The maximum deposited X-ray energy per pulse (E_{max}) was 0.7 MeV and the total deposited X-ray energy (E_{total}) was 3.5 MeV.

Table 2 Occurrence of X-Rays as a Function of Return Stroke Peak Current

Peak Current Range (kA)	Number of Strokes	Number of Strokes with Detectable X-Rays[a]	Percentage
0 – 10	2	0 (0 + 0)	0
10 – 20	18	4 (3 + 1)	22
20 – 30	18	4 (2 + 2)	22
30 – 40	14	7 (4 + 3)	50
40 – 50	9	5 (4 + 1)	56
50 – 60	9	5 (5 + 0)	56
60 – 70	2	2 (2 + 0)	100
70 – 80	5	5 (4 + 1)	100
80 – 90	2	2 (1 + 1)	100
90 – 100	2	1 (0 + 1)	50
>100	3	3 (2 + 1)	100
Total	84	38	45

[a]The first and second numbers in the parentheses indicate the occurrence of X-ray bursts and single pulses, respectively.

Table 3 Occurrence of X-Rays as a Function of Distance from Lightning Channel

Distance (km)	Number of Strokes	Number of Strokes with Detectable X-Rays[a]	Percentage
0 – 0.5	3	3 (2 + 1)	100
0.5 – 1.0	19	12 (10 + 2)	63
1.0 – 1.5	38	16 (12 + 4)	42
1.5 – 2.0	24	7 (3 + 4)	29
Total	84	38	45

[a]The first and second numbers in the parentheses indicate the occurrence of X-ray bursts and single pulses, respectively.

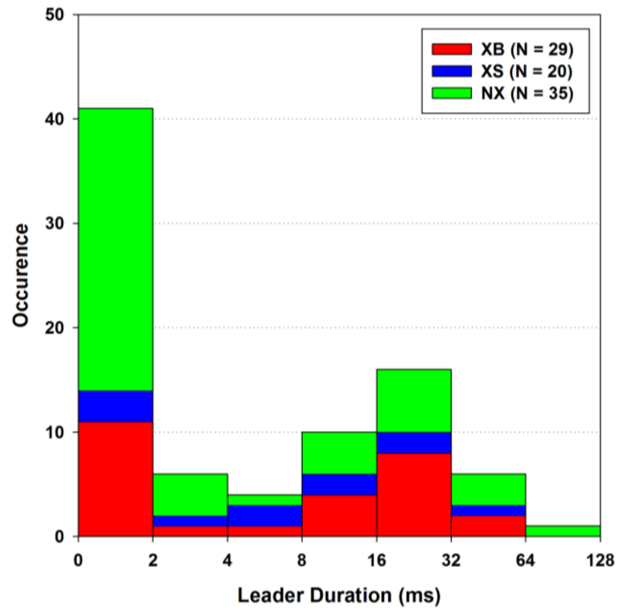


Figure 2. Occurrence of X-rays as a function of leader duration. XB, XS, and NX denote X-ray burst, single X-ray pulse, and no X-rays, respectively.

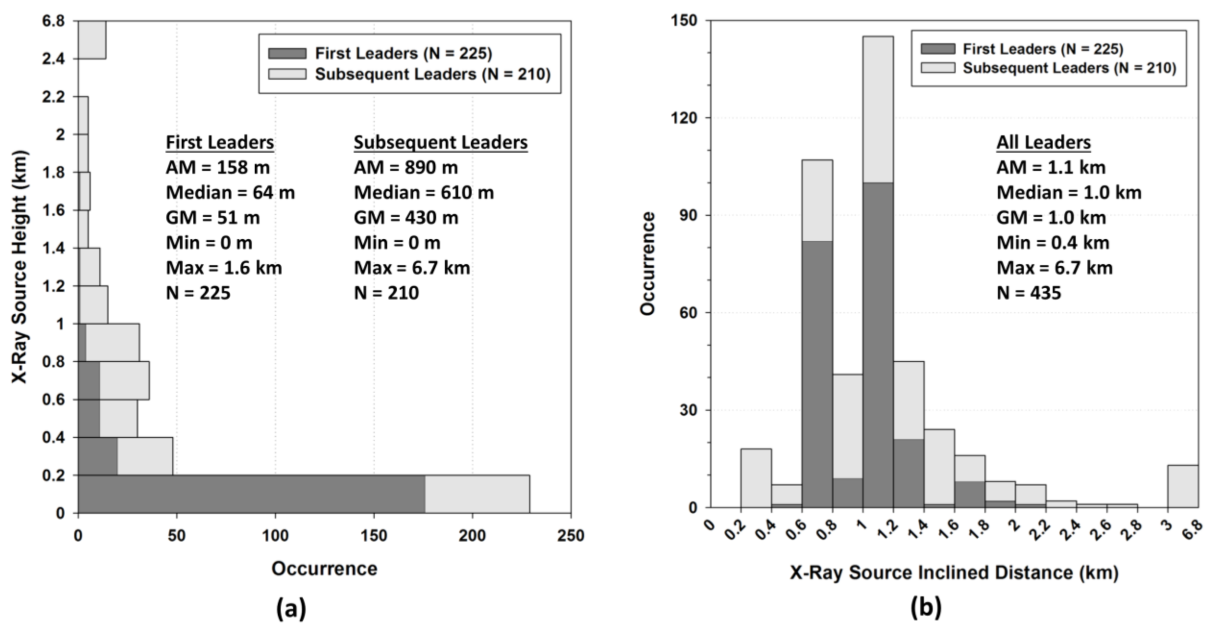


Figure 3. Occurrence of (a) X-ray source heights and (b) X-ray source inclined distances for an assumed 7.5-km total channel length. Note that, in both (a) and (b), the last bin is actually wider than the other histogram bins.

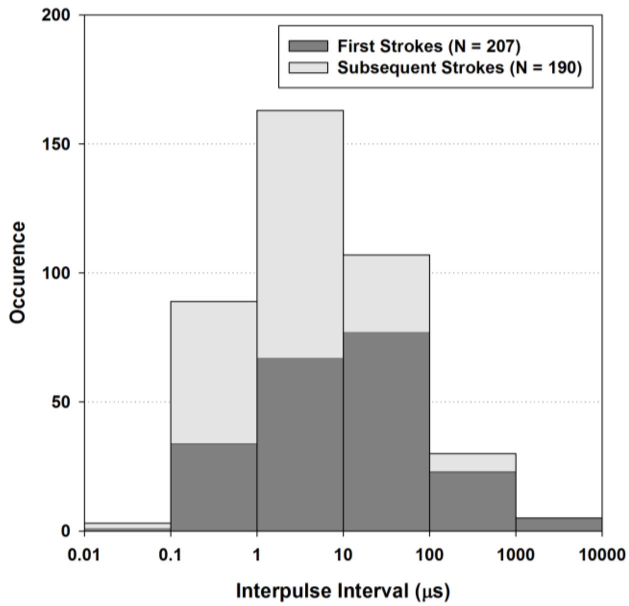


Figure 4. Histogram of intervals between discernible X-ray pulses for first and subsequent strokes.

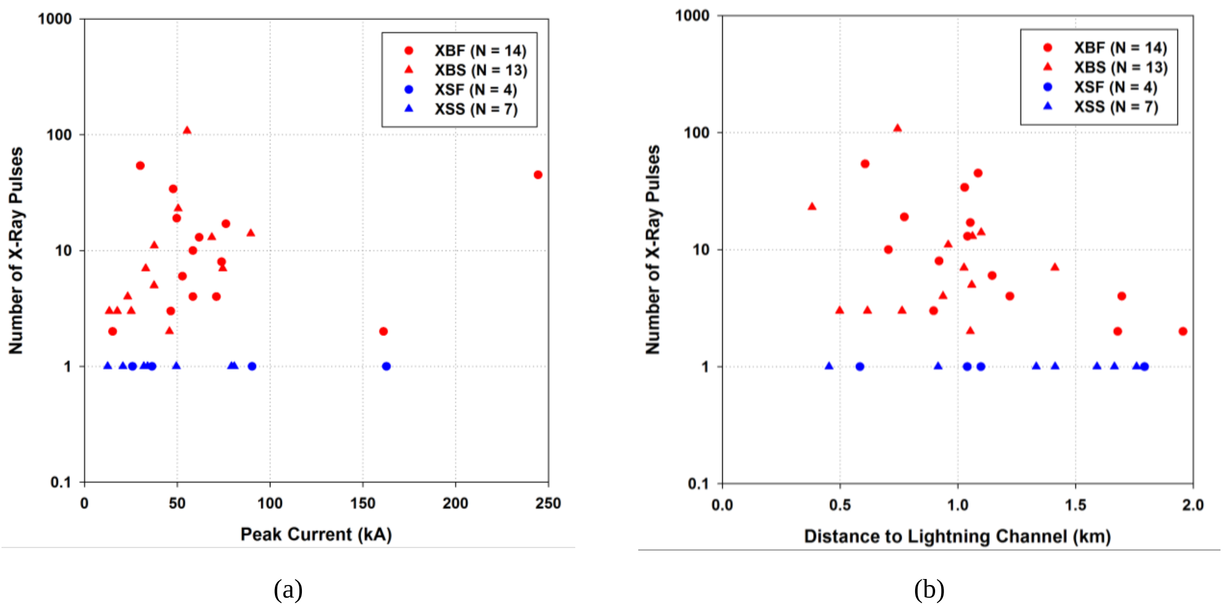
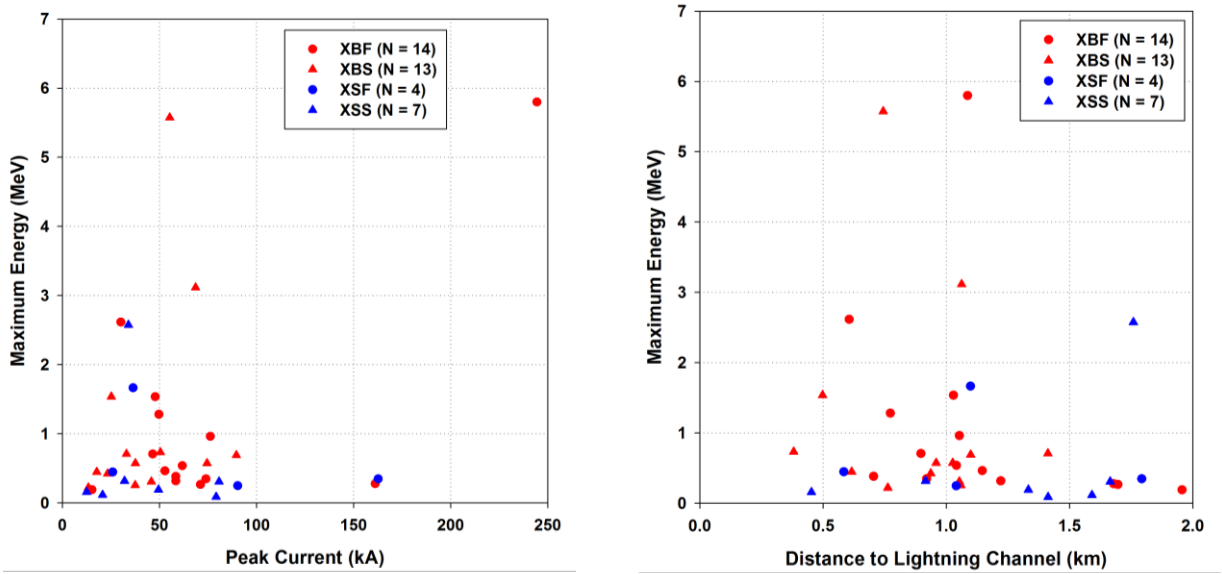
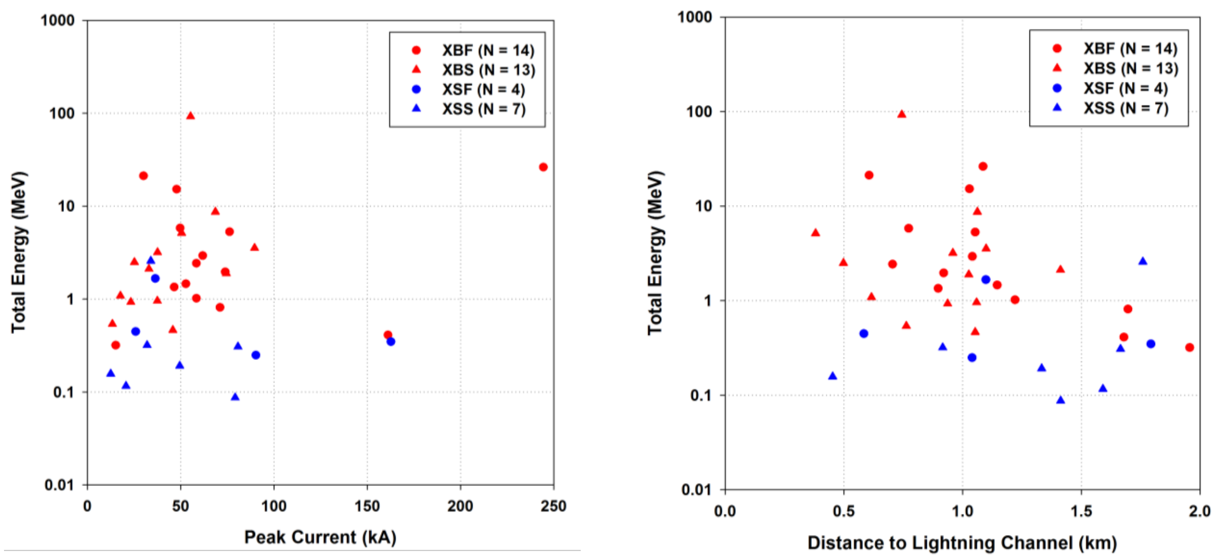


Figure 5. Number of discernible X-ray pulses versus (a) return-stroke peak current and (b) distance to the lightning channel. XBF, XBS, XSF, and XSS denote X-ray burst in first stroke, X-ray burst in subsequent stroke, single X-ray pulse in first stroke, and single X-ray pulse in subsequent stroke, respectively.



(a) (b)

Figure 6. Maximum deposited X-ray energy per pulse (not necessarily for a single photon) versus (a) return-stroke peak current and (b) distance to the lightning channel. XBF, XBS, XSF, and XSS denote X-ray burst in first stroke, X-ray burst in subsequent stroke, single X-ray pulse in first stroke, and single X-ray pulse in subsequent stroke, respectively.



(a) (b)

Figure 7. Total deposited X-ray energy (sum of energies of all pulses) versus (a) return-stroke peak current and (b) distance to the lightning channel. XBF, XBS, XSF, and XSS denote X-ray burst in first stroke, X-ray burst in subsequent stroke, single X-ray pulse in first stroke, and single X-ray pulse in subsequent stroke, respectively.