2008 20th International Lightning Detection Conference
21-23 April • Tucson, Arizona, USA
2nd International Lightning Meteorology Conference
24-25 April • Tucson, Arizona, USA

CHARACTERISTICS OF CLOUD-TO-GROUND LIGHTNING IN WARM-SEASON THUNDERSTORMS IN THE GREAT PLAINS

S.A. Fleenor[*], C. J. Biagi[1], K. L. Cummins[2], E.P. Krider
Institute of Atmospheric Physics, University of Arizona, Tucson, AZ

[1]Currently, Electrical and Computer Engineering, University of Florida, Gainesville, FL
[2]Also, Vaisala, Inc., Thunderstorm Business Unit, Tucson, AZ

1. INTRODUCTION

In July, 2005, a field campaign was conducted in the Great Plains of eastern Colorado, western Kansas and western Nebraska to obtain 60 field/sec video imagery of lightning in correlation with reports from the U.S. National Lightning Detection Network (NLDN). This region was chosen because prior studies have shown that it contains high fractions of both positive and negative flashes. In our campaign, lightning was recorded using digital video cameras that were synchronized to GPS time (with 16.7 msec resolution, see Parker and Krider (2003) and Biagi et al. (2007)), and the results were compared with NLDN reports that provided the time, polarity, location, and an estimate of the peak current (I_p) for each stroke [Cummins et al., 1998]. In this paper, we will discuss the characteristics of the negative, positive, and bipolar flashes recorded during the campaign.

2. Methodology

2.1 Video Recording System

Lightning return strokes were recorded using one or two Canon GL1 digital video camcorders with 720x480 pixel resolution. During the data analysis, the standard 30 video frames per second were de-interlaced to obtain 60 fields per second that could be viewed on a standard video monitor (Parker and Krider, 2003). The camera exposure time was set to 16.7 ms to eliminate any dead time between fields. Different strokes that followed the same channel to ground may not have been resolved by the video camera if they had an interstroke interval less than 33 ms. Each video field was time-synchronized to GPS time, and the GPS times were used to correlate video strokes with NLDN reports. A more detailed discussion of the video recording system,and the methods of analysis can be found in Parker and Krider (2003), Biagi et al. (2007), and Fleenor et al. (2008).

In this study, a ground stroke was considered to have occurred within a particular video field if that field contained a clearly visible channel between the cloud and ground. Strokes that remained luminous for two or more consecutive fields were assumed to have a continuing luminosity, and in some cases, the appearance of continuing luminosity may have been produced by an unresolved subsequent stroke. Any increases in the continuing luminosity of the channel were assumed to be M components (Thottappillil et al., 1995).

2.2 NLDN Data

The NLDN data used in this study were taken from an archived database and were provided by the Vaisala Thunderstorm Unit in Tucson, AZ. The NLDN reports consisted of time, location, type of impulse, and an estimate of the polarity and peak current (I_p) of each stroke (Cummins et al., 1998).

The peak current is estimated using a linear scaling of the range-normalized (propagation corrected) peak field values for all time-consistent (within ~10 µs) reports by the NLDN sensors that are within 625 km of the stroke location (Cummins et al., 1998). The scaling value was derived from an analysis of rocket triggered lightning (RTL), which produces CG strokes that are similar to natural subsequent strokes in existing channels (Rakov, 2001). The RMS error in the NLDN peak current estimates for 55 triggered, negative subsequent strokes was 2.3 kA using the propagation model parameters that were implemented in the NLDN as of July 2004 (Cummins et al., 2006). It is possible that the proper scaling value for positive strokes and negative first strokes is larger than the value derived from RTL due to the lower propagation speed for these strokes (Idone and Orville, 1982; Mach and Rust, 1993), but the magnitude of such an error is not yet known.

Table 1. **Summary of Lightning Measurements in the Great Plains in 2005. Sessions highlighted in gray were dominated by negative CG flashes and sessions not highlighted were dominated by positive CG flashes.**

Session	Date 2005	Video Flashes	Flashes (%) Reported by NLDN	Video Strokes	Strokes (%) Reported by NLDN	Mean Video Multiplicity	Session Polarity (%)
1	3 July	31	29 (94)	75	60 (80)	2.42	Negative (100)
2	4 July	10	7 (70)	10	7 (70)	1.00	Positive (100)
3	5 July	16	15 (94)	25	18 (72)	1.56	Positive (94)
4	5 July	4	4 (100)	5	5 (100)	1.25	Positive (100)
5	6 July	20	19 (95)	58	46 (80)	2.85	Negative (100)
6	6 July	12	12 (100)	13	12 (92)	1.08	Positive (92)
7	6 July	23	19 (83)	51	40 (78)	2.22	Negative (100)
8	6 July	3	3 (100)	15	10 (67)	5.00	Negative (100)
9	7 July	30	28 (93)	33	31 (94)	1.10	Positive (100)
10	7 July	8	8 (100)	33	26 (79)	4.13	Negative (100)
11	7 July	13	12 (92)	14	13 (93)	1.08	Positive (100)
12	10 July	6	5 (83)	6	5 (83)	1.00	Positive (100)
13	10 July	45	42 (93)	49	43 (88)	1.09	Positive (98)
14	11 July	88	78 (89)	105	93 (89)	1.19	Positive (92)
15	11 July	12	10 (83)	12	10 (83)	1.00	Positive (100)
16	11 July	6	6 (100)	6	6 (100)	1.00	Positive (100)
17	13 July	15	14 (93)	37	32 (86)	2.47	Negative (100)
	Positives	**229**	**204 (89)**	**239**	**210 (88)**	**1.04**	
	Negatives	**109**	**103 (94)**	**296**	**238(80)**	**2.72**	
	Bipolars	**4**	**4 (100)**	**9**	**9 (100)**	**2.25**	
	All Data	**342**	**311 (91)**	**547**	**457 (84)**		

The NLDN groups separate strokes into flashes when all strokes occur within 10 km of the first stroke and the time-interval between strokes is less than 500 ms (Cummins et al., 1998). To be consistent with the NLDN, we used these same criteria when we grouped video strokes into video flashes.

3. Results

3.1 Negative Flashes

Six of the 17 recording sessions that are summarized in Table 1 were dominated by negative NLDN reports, and these contained a total of 109 flashes and at least 296 video strokes. The NLDN reported 103 out of the 109 flashes and 238 out of the 296 strokes recorded on video. As noted in Table 1, this means that the NLDN had an average negative flash DE of 103/109, or 94%, and an average negative stroke DE of 238/296, or 80%. A stroke recorded on video that was not reported by the NLDN was presumed to have a negative polarity if that stroke was part of a negative polarity flash as reported by the NLDN.

3.1.1 Estimated Negative Peak Current

Figure 1 shows distributions of the estimated peak current, $|I_p|$, for all negative first strokes, negative subsequent strokes that formed a new ground contact (NGC), and the negative subsequent strokes that remained in a pre-existing channel (PEC). The mean and median values of $|I_p|$ for first strokes were 23.3 kA and 19.6 kA, respectively. Note that the medians for first strokes are 9% larger than the medians of subsequent strokes that form a NGC and 29% larger than the median of subsequent strokes remaining in a PEC.

There were 26 negative strokes that had an $|I_p| \leq 10$ kA. Eight out of these 26 strokes were the first stroke in a flash, 5 were subsequent strokes that formed a NGC, and 13 were subsequent strokes that remained in a PEC. The NLDN reported only 2 negative strokes (1 first stroke and 1 subsequent stroke that formed a NGC) with an $|I_p| < 5$ kA, a result that is consistent with model-based estimates of the NLDN detection threshold (4-6 kA) in the GP (see Cummins et al., 2006, Figure 5).

3.1.2 Negative Multiplicity and Number of Ground Contacts

Values of the video multiplicity (number of strokes per flash) of negative flashes are summarized in Figure 2. It should be noted that 41 out of 103 (40%) of the negative CG flashes produced just a single-stroke. Because the time-resolution of the video camera was limited to 16.7 ms, the multiplicities in Figure 3 are likely to be underestimated. Biagi et al. (2007) have determined that the video camera underestimates the true negative multiplicity in southern Arizona by about 11%. If we assume that the same fraction of strokes is not resolved in the Great Plains, then the true multiplicity of negative strokes is about 3.14 strokes/flash in this region. This result is lower than what Biagi et al. (2007) found in Southern Arizona 2003-2004 (3.82), and higher than the value these authors found in Texas and Oklahoma 2003-2004 (2.66). It should be noted that 7 out the 8 (87%) negative first strokes that had an $|I_p| \leq 10$ kA were single stroke flashes, which is an even larger fraction than what Biagi et al. (2007) found for low-amplitude negative flashes in Southern Arizona (45%) and in Texas and Oklahoma (52%).

There were 34 negative flashes that produced two or more separate and distinct ground contacts, and the distribution of the number of contacts in these flashes is shown in Figure 3. The average number of ground contacts per negative flash was 1.56.

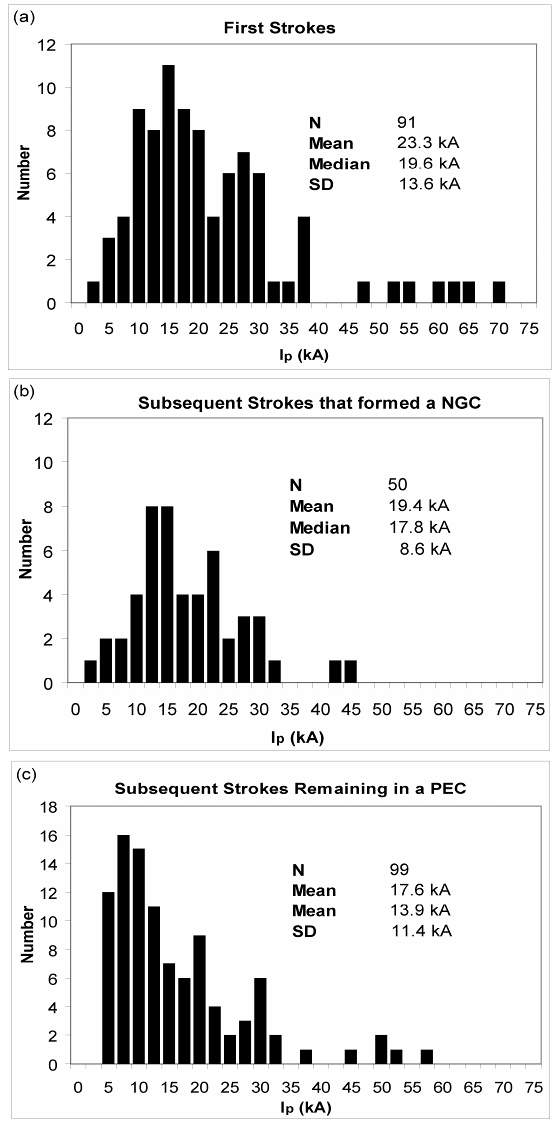

Figure 1. Distributions of I_p for (a) negative first strokes, (b) negative strokes that create a new ground contact (NGC), and (c) negative strokes that remain in a pre-existing channel (PEC).

3.2 Positive Flashes

Table 1 shows that 11 out of the 17 recording sessions in the Great Plains were dominated by positive CG flashes. There were a total of 229 positive flashes recorded on video, and these contained at least 238 video strokes. A total of 180 out of the 238 video strokes, or 76%,exhibited

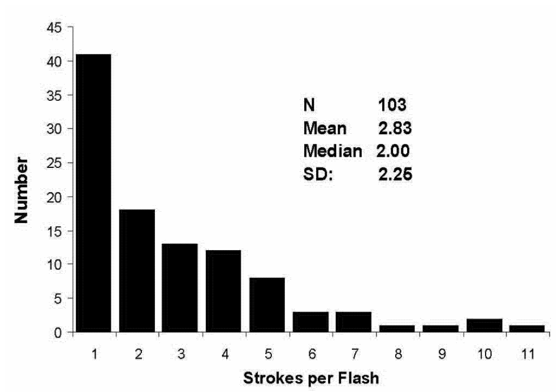

Figure 2. Video multiplicity of negative flashes in the Great Plains. The mean multiplicity was 2.9 after correcting for the finite time-resolution of the video camera.

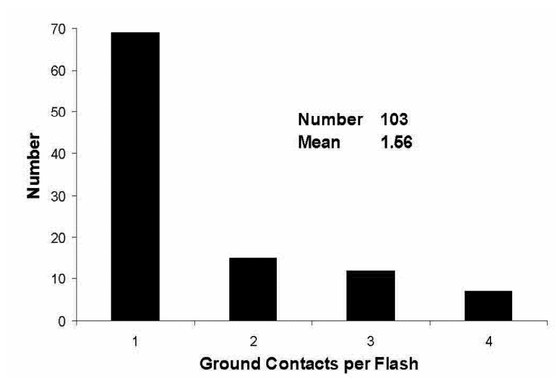

Figure 3. Number of different ground contacts per negative flash.

a continuing luminosity (i.e. the stroke remained luminous for 2 or more video fields).

There were 204 flashes containing 210 strokes that were correlated with positive NLDN reports; therefore, the positive NLDN flash and stroke DE were 204/229, or 89%, and 210/238, or 88%, respectively. There were 2 single-stroke flashes seen on video that did not trigger the NLDN or the LASA sensors, and these were assumed to have a positive polarity because they occurred during a positive dominated session.

3.2.1. Estimated Peak Current, I_p

The distribution of I_p for 204 positive first strokes is shown in Figure 4. The mean I_p was 48.8 kA, and the median was 44.8 kA. There were 16 positive first strokes recorded on video that had an I_p between 5 kA and 20 kA, and 5 had an $I_p >$

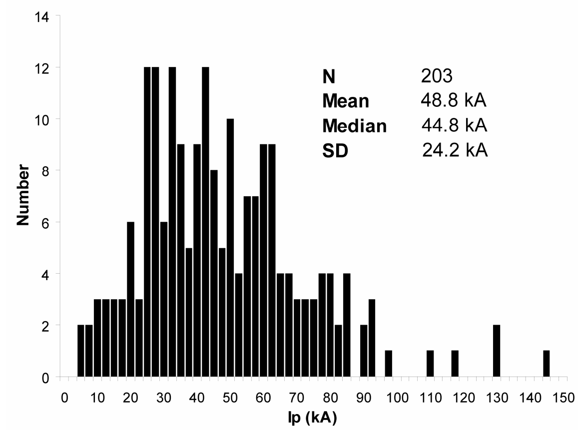

Figure 4. Distribution of the estimated peak current, I_p, for all positive first strokes. Four first strokes had an I_p between 5 and 10 kA, and 16 first strokes had an $I_p \leq 20$ kA.

100 kA. The 9 positive subsequent strokes had a mean I_p of 36.1 kA, and a median I_p of 26.6 kA.

3.2.2. Multiple-Stroke Positive Flashes

Only 9 out of 204 (2 %) of the positive flashes recorded on video contained multiple strokes, and each of these had just 2 strokes; therefore, the mean positive multiplicity was 1.04. Within this sample of 9 subsequent strokes, 4 produced a NGC, and 5 remained in a PEC. The polarity of 17 of the 18 first and subsequent strokes was confirmed using the LASA waveforms, and 15 of the 18 strokes were correlated with an NLDN report. It should be noted that one of the subsequent strokes did not trigger the LASA system, and it is possible that this stroke was actually an M-component.

Figure 5 shows the time development and amplitude of 8 of the 9 multiple-stroke positive flashes, each having just 2 strokes. Note that all of the subsequent strokes remaining in a PEC occurred between 27 to 37 ms after the first stroke. The subsequent strokes that produced a NGC had interstroke intervals ranging from 13 ms to 155 ms.

3.3. Bipolar Flashes

There were 4 bipolar flashes in our dataset, and each of these began with a positive first stroke that was followed by 1 or 2 negative strokes. The time development, amplitudes, and polarities of all the strokes in these flashes are shown in Figure 6.

Note that the intervals between the first and second strokes range from 43 ms to 278 ms and that 4 of the 5 of these intervals are at least 50 ms greater than the interstroke-intervals in the two-stroke positive flashes (Figure 5). It should also be noted that 2 of the 4 second negative strokes remained in a PEC.

Jerauld et al. (2004) reported one bipolar 3-stroke flash that began with 2 positive strokes, and was followed by 1 negative stroke. The interstroke interval between the 2 positive strokes was 53 ms and the interval between the last two strokes was 525 ms. Baranski and Bodzak (2006) have analyzed 8 bipolar flashes, 3 of which began with a positive first stroke, and were followed by a negative stroke. Two of the latter flashes had interstroke intervals (6.4 ms, 14.2 ms) that were considerably shorter then our intervals.

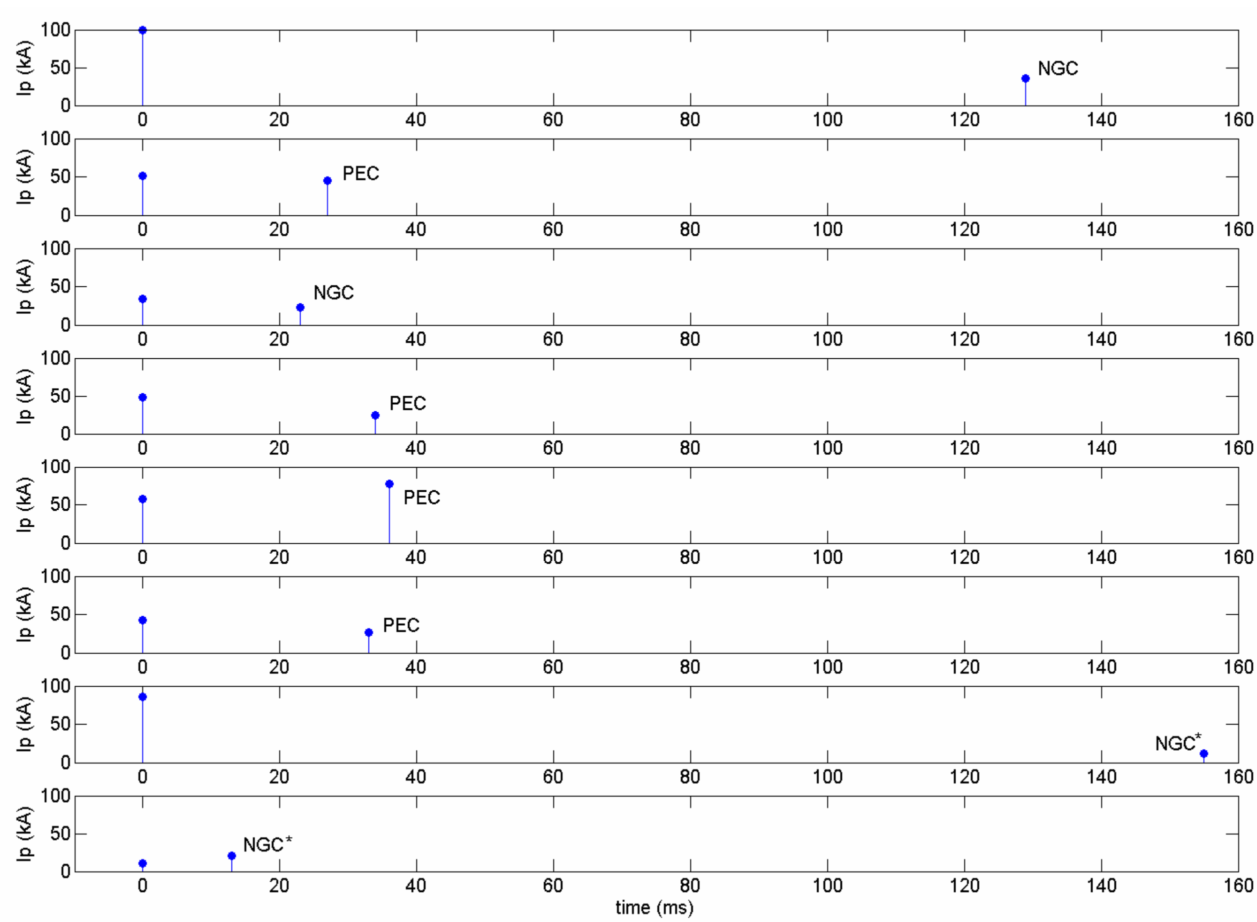

Figure 5. Relative time of occurrence and amplitude of the strokes in 8 multiple-stroke positive flashes recorded on video. Strokes that created a new ground contact are labeled NGC, and the strokes that remained in a pre-existing channel are labeled PEC. The geometric mean interstroke interval is 27 ms, and the median interstroke interval is 33.5 ms.

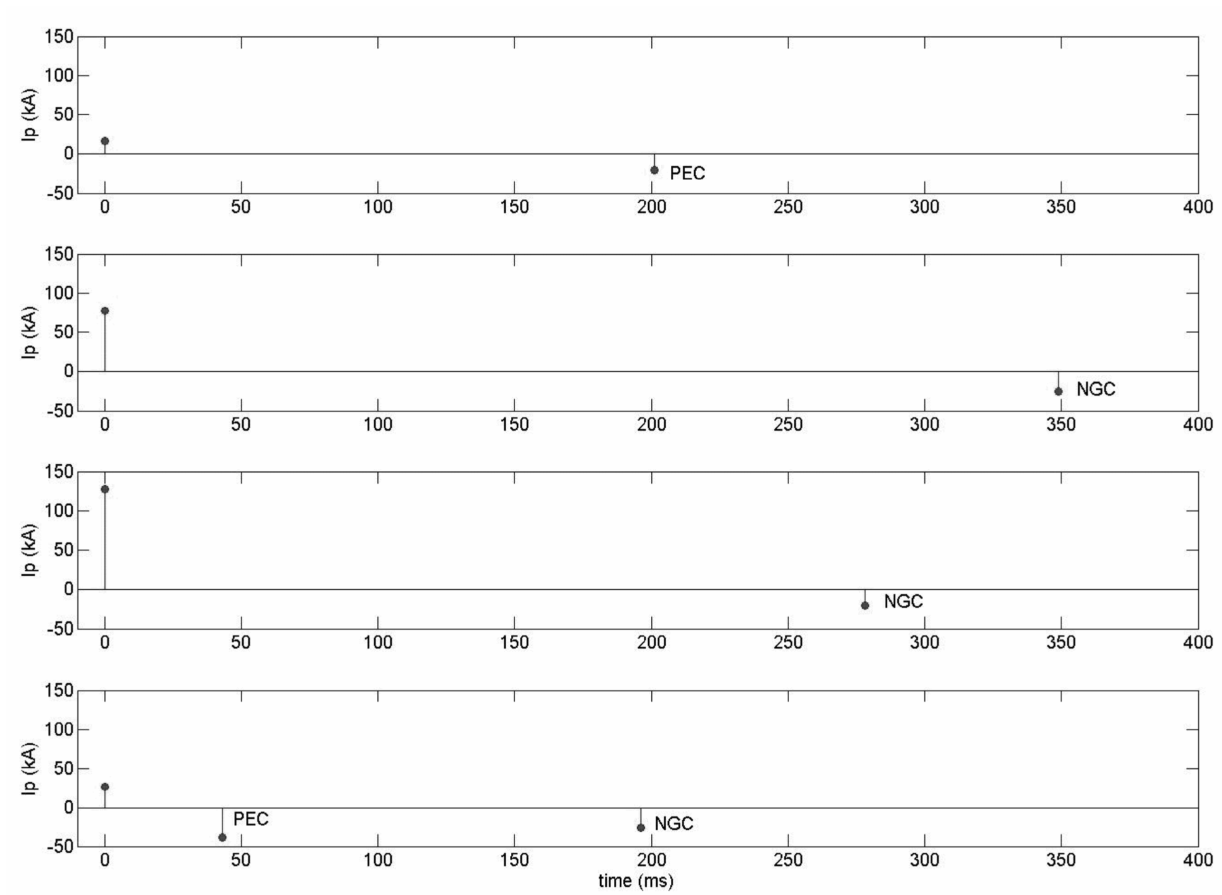

Figure 6. Relative time of occurrence and amplitude of the strokes in 4 bipolar flashes recorded on video. Strokes that created a new ground contact are labeled NGC, and the strokes that remained in a pre-existing channel are labeled PEC.

4. Discussion

Analyses of 342 cloud-to-ground flashes recorded on video in the Great Plains have provided new insights into the occurrence and characteristics of negative and positive flashes in that region. The median I_p for negative first strokes was -19.6 kA, which is 14% larger than the median Biagi et al. (2007) found in Southern Arizona in 2003-2004 (-16.9 kA), and 30% larger than the value found in Texas and Southern Oklahoma in 2003-2004 (-13.8 kA). It should be noted that the above medians are significantly lower than the values commonly found in the engineering literature [Rakov and Uman, Ch. 1; Berger, 1975]. Given that the NLDN misses primarily low-amplitude strokes [Cummins et al., 1998; Jerauld et al., 2005; and Biagi et al., 2007], the actual medians of $|I_p|$ are probably even lower than the above values. Since the accuracy of the estimated I_p for first strokes derived from lightning locating systems has not yet been confirmed, this finding may not be significant; however, it is interesting to note that the median values of I_p for negative subsequent strokes that remain in a pre-existing channel (-13.7 kA) are in excellent agreement with prior measurements of subsequent strokes in both natural and rocket-triggered lightning [Fisher et al., 1993; Jerauld et al., 2005]. This finding may be explained by a slower return stroke velocity for negative first strokes, as suggested by Idone and Orville (1982).

The characteristics of positive CG flashes are not as well documented in the lightning literature as negative flashes because most warm-season thunderstorms produce very few positive flashes. The 204 video-validated positive flashes in our dataset represent about 2/3 of the CG flashes that were recorded in our 2005 campaign. Berger (1975) analyzed a total of 26 positive flashes, and obtained a median peak current of 35 kA. These flashes were a mixture of discharges produced by upward propagating leaders from a tower and flashes that were initiated by downward propagating leaders. The 35 kA median that Berger obtained for positive first strokes is 22 % lower than our median I_p (44.8 kA). If the typical return stroke velocity for positive strokes is a factor-of-two lower than for negative strokes (as suggested by Mach and Rust (1993)), then the median peak current for the positive flashes in this study could be much larger than 44.8 kA.

Saba et al. (2007) analyzed 38 positive flashes that were recorded using high speed video cameras in Brazil in combination with CG lightning sensors similar to those in the NLDN. These authors reported a median I_p of 28 kA for first strokes and a median I_p of 15 kA for subsequent strokes, values that are even lower than the medians obtained by Berger. As discussed above, the true median I_p in the Great Plains could be slightly lower than what we are reporting here because the NLDN misses some low-amplitude CG strokes, and the strokes that are recorded on video may have a slight bias towards higher I_p values. We view the latter bias as unlikely since the median I_p we obtained for positive first strokes (44.8 kA) is 44% larger than the median for negative first strokes (-19.6 kA).

As expected, the average video multiplicity for positive flashes (1.04) was significantly lower than the measured value for negative flashes (2.83), and the negative value after correcting for camera resolution (3.14). Table 2 shows the values of positive multiplicities reported in other studies. It should be noted that Heidler and Hopf (1998) and Saba et al. (2007) have significantly higher values than what we found in the Great Plains. This may be because of the small number of positive flashes recorded in the earlier studies.

The geometric mean interstroke interval between positive CG strokes recorded on video and correlated with the NLDN was 27 ms. This value is 29 ms less than the geometric mean between negative strokes (Rakov and Uman, 2003, Ch. 4). Other studies (see Table 3) have found interstroke intervals that are 3 to 6 times larger than our value. Given the small number of multiple-stroke positive flashes that were found in the other studies, this difference may not be significant.

There were 4 bipolar flashes in our dataset. These flashes are rare, and the few examples that have been previously documented in the literature are discussed by Rakov (2003). It should be noted that our positive interstroke intervals are significantly less than the interstroke intervals in bipolar flashes (compare Figure 5 and Figure 6).

Table 2. Summary of the number and mean multiplicities of positive CG flashes.

	N	Mean (ms)
Fuquay (1972)	75	1.03
Heidler and Hopf (1998)	45	1.4
Saba et al. (2007)	39	1.33
Present Study	204	1.04

Table 3. Summary of the geometric mean (GM), mean, and standard deviations (SD) of the interstroke intervals in positive CG flashes.

	N	GM (ms)	Mean (ms)	SD (ms)
Fuquay (1982)	2	170	170	14
Cooray and Perez (1994)	29	92	64	-
Heidler and Hopf (1998)	16	101	120	97
Saba et al. (2007)	13	117	168	131
Present Study	9	27	50	54

ACKNOWLEDGEMENTS

This work has been supported in part by the NASA Kennedy Space Center, Grant NNK06EB55G, and Vaisala Thunderstorm, Tucson, AZ. We also thank John Cramer of Vaisala Thunderstorm for NLDN data processing.

REFERENCES

Baranski, P., Bodzak, P., 2006. Some observations of bipolar flashes during summer thunderstorms near Warsaw. Acta Geophysica. 54, 1, 71-89.

Berger, K., Anderson, R.B., Kroninger, H., 1975. Parameters of lightning flashes. *Electra*. 80, 23-37.

Biagi, C.J., Cummins, K.L., Kehoe, K.E., Krider, E.P., 2007. National Lightning Detection (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003-2004. *J. Geophys. Res.* 112, D05208, doi:10.1029/2006JD007341.

Cooray, V. and Perez, H., 1994. “Some features of lightning flashes observed in Sweden,” *J.*

Geophys. Res., vol. 99, no. D5, pp. 10 683-10 688.

Cummins, K.L., Murphy, M.J., E.A. Bardo, Hiscox, W.L., Pyle, R.B., Pifer, A.E., 1998. A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res*. 103*,* 9038-9044.

Cummins, K.L., Cramer, J.A., Biagi, C.J., Krider, E.P., Jerauld, J., Uman, M.A., Rakov, V.A., 2006. The U.S. National Lightning Detection Network: post-upgrade status, second conference on meteorological applications of lightning data, American Meteorological Society meeting, Atlanta GA, January 29 - February 2, 2006, paper 6.1.

Fisher, R.J.,. Schnetzer, G.H, Thottappillil, R.,. Rakov, V.A, Uman, M.A., Goldberg, J.D., 1993. Parameters of triggered-lightning flashes in Florida and Alabama. *J. Geophys. Res.* 98, 22, 887 - 22,902.

Fuquay, D.M., Taylor, A.R, Hawe, R.G., Schimd, Jr. C.W., 1972. Lightning discharges that caused forest fires. *J. Geophy. Res.* 77, 2156-2158.

Fuquay, D.M., 1982. Positive cloud-to-ground lightning in summer thunderstorms. *J. Geophys. Res.*, 87, No. C9, 7131-7140.

Heidler, F., Hopf, C., 1998. Measurement results of the electric fields in cloud-to-ground lightning in nearby Munich, Germany. IEEE Transactions on EMC. 40, 4, 436-443.

Idone, V.P., Orville, R.E., 1982. Lightning return stroke velocities in the Thunderstorm Research International Program (TRIP). *J. Geophys. Res.* 87, 4903-15.

Idone, V.P., Orville, R.E., 1985. Correlated peak relative light intensity and peak current in triggered lightning subsequent return strokes. J. Geophys. Res. 90, 6159-6164.

Jerauld, J., Uman, M.A., Rakov, V.A., Rambo, K.J., Jordan, D.M., 2004. A triggered lightning flash containing both negative and positive strokes. *Geophys. Res. Lett.* 31, L08104, doi: 10.1029/2004GL019457.

Jerauld, J., Rakov, V.A., Uman, M.A., Rambo, K.J., Jordan D.M., Cummins, K.L., and Cramer, J.A., 2005. An evaluation of the performance characteristics of the U.S. National Lightning Detection Network in Florida using rocket triggered lightning, *J. Geophys. Res.* 110, D19106, doi:10.1029/2005JD005924.

Mach, D.M., Rust, W.D., 1993. Two-dimensional velocity, optical risetime, and peak current estimates for natural positive lightning return strokes. *J. Geophys. Res*. 98, 2635-8.

Parker, N.G., Krider, E.P., 2003. A portable, PC-based system for making optical and electromagnetic measurements of lightning. *J. Appl. Meteorol.* 42, 739-751.

Rakov, V.A., Uman, M.A., 1994. Origin of lightning electric field signatures showing two return-stroke waveforms separated in time by a millisecond or less. *J. Geophys. Res.* 99, 8157-8165.

Rakov, V.A., 2001. Transient response of a tall object to lightning. IEEE Trans. on EMC. 43, 654-661

Rakov, V.A, 2003. A review of positive and bipolar lightning discharges. *Bull. Amer. Meteor. Soc.* 84**,** 6, 767-776, doi: 10.1175/BAMS-84-6-767.

Rakov, V.A., Uman, M.A., 2003. Lightning: Physics and Effects, Cambridge University Press, Cambridge.

Saba, M.M.F., Ballarotti, M.G., Campos, L.Z.S., Pinto, Osmar Jr., 2007. High-speed video observations of positive lightning., IX International Symposium on Lightning Protections, Foz do Iguacu, Brazil, 26-30 November.

Thottappillil, R., Goldberg, J.D., Rakov, V.A., Uman, M.A., Fisher, R.J., Schnetzer, G.H., 1995. Properties of M-components from currents measured at triggered lightning channel base. *J. Geophys. Res.* 100, 25 711-20.