JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D05208, doi:10.1029/2006JD007341, 2007

National Lightning Detection Network (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003–2004

Christopher J. Biagi,[1] Kenneth L. Cummins,[1,2] Kenneth E. Kehoe,[1,3] and E. Philip Krider[1]

Received 24 March 2006; revised 18 September 2006; accepted 22 September 2006; published 9 March 2007.

[1] Four field campaigns were conducted in southern Arizona (AZ) and in northern Texas and southern Oklahoma (TX-OK) in 2003 and 2004 to evaluate the performance of the U.S. National Lightning Detection Network™ (NLDN) in detecting cloud-to-ground (CG) lightning after an upgrade in 2002 and 2003. The 2-year average flash detection efficiency (DE) in AZ was 93% (1024/1097), and the measured (first plus subsequent) stroke DE was 76% (2746/3620). The corresponding values in TX-OK were 92% (338/367) and 86% (755/882), respectively. After correcting for the time resolution of the video camera (16.7 ms), we estimate that the actual NLDN stroke DE and video multiplicities were about 68% and 3.71 in AZ and 77% and 2.80 in TX-OK. The average DE for negative first strokes (92%) was larger than the measured DE for subsequent strokes that produced a new ground contact (81%) and the DE for subsequent strokes that remained in a preexisting channel (67%). The primary cause of the NLDN missing strokes was that the peak of the radiated electromagnetic field was below the NLDN detection threshold. The average estimated peak current (I_p) of negative first strokes and the average multiplicity of negative flashes varied from storm to storm and between the two regions, but this variability did not affect the DE as long as the recording sessions had more than 60 flashes. By analyzing the NLDN locations of subsequent strokes that remained in the same channel as the first stroke we infer that the median random position error of the NLDN was 424 m in AZ and 282 m in TX-OK. An evaluation of the classification of lightning type by the NLDN (i.e., CG stroke versus cloud pulse) showed that 1.4–7% (6/420 to 6/86) of the positive NLDN reports with an $I_p \leq 10$ kA in TX-OK were produced by CG strokes; 4.7–26% (5/106 to 5/19) of the positive reports with 10 kA < $I_p \leq 20$ kA were CGs; and 67–95% (30/45 to 30/32) of the reports with $I_p \geq +20$ kA were CG strokes. Some 50–87% (52/104 to 52/60) of the negative, single-stroke NLDN reports in AZ and TX-OK with $|I_p| \leq 10$ kA were produced by CG flashes. Both the upper and lower bounds in these classification studies have observational biases.

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

1. Introduction

[2] During 2002 and 2003, the U.S. National Lightning Detection Network™ (NLDN, operated by the Vaisala Thunderstorm Unit, Tucson, Arizona) [*Cummins et al.*, 1998] underwent a system-wide upgrade [*Cramer et al.*, 2004]. The objectives of the upgrade were (1) to provide enhanced detection efficiency (DE) and location accuracy near the boundaries of the network, (2) to increase network reliability, (3) to reduce operating and maintenance costs, and (4) to detect at least some cloud discharges. The previous NLDN configuration (1995–2002) contained both time-of-arrival LPATS sensors and combined magnetic direction-finding and time-of-arrival IMPACT sensors [*Cummins et al.*, 1998]. In the recent upgrade, all sensors were replaced by improved IMPACT-ESP sensors, and 8 additional sensors were added to the network [*Cramer et al.*, 2004]. The ESP sensors have improved analog signal processing, higher gain, and lower noise, all of which provide better detection of low-amplitude signals. Vaisala has estimated that the NLDN now provides an overall cloud-to-ground (CG) flash detection efficiency (DE) that is better than 90% throughout the continental U.S. and that the DE for all CG strokes is in the range of 60 to 80% [*Cramer et al.*, 2004].

[3] In order to check the NLDN performance after the upgrade, we made independent video recordings of lightning flashes together with GPS time in four separate field campaigns in southern Arizona (AZ) and northern Texas and southern Oklahoma (TX-OK) during 2003 and 2004, in

[1]Institute of Atmospheric Physics, University of Arizona, Tucson, Arizona, USA.
[2]Also at Thunderstorm Business Unit, Vaisala, Inc., Tucson, Arizona, USA.
[3]Now at Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, Oklahoma.

0148-0227/07/2006JD007341$09.00

a fashion similar to *Idone et al.* [1998]. When possible, optical (O) and electric field (E) waveforms were also recorded to augment the video records and to obtain better time resolution [*Parker and Krider*, 2003]. The flash and stroke DEs were computed by comparing the NLDN reports of CG flashes and strokes with those recorded on video and, if possible, the O and E waveforms.

[4] The tendency of the NLDN to misclassify some cloud pulses as low-amplitude, positive CG strokes has been documented since 1998 [*Cummins et al.*, 1998; *Wacker and Orville*, 1999]. Here, we will define a "small positive flash" to be a single-stroke, positive NLDN report that has an estimated peak current, I_p, less than +20 kA. Because of the difficulty in obtaining ground truth data, the classification of this type of event has not been previously investigated beyond an initial finding that most small positive reports with an I_p < +10 kA were very likely to be cloud pulses. The data that we obtained in TX-OK during 2003 and 2004 have been analyzed to determine the type of lightning that produced small positive NLDN reports as a function of I_p.

[5] With the installation of the IMPACT-ESP sensors during the 2002–2003 upgrade, it was expected that the negative flash multiplicity (number of strokes per flash) would increase because of the improved ability of the NLDN to detect low-amplitude strokes. Although an increase did occur in most geographic regions, there were some areas that showed no change or even a decrease in the average negative multiplicity, particularly in the central and southeastern U.S. [*Cummins and Bardo*, 2004]. One reason for a decrease could be that the NLDN is now detecting more low-amplitude, single-stroke CG flashes with an I_p between -10 kA < I_p < 0 kA (which we will term "small negative" flashes), and this population offsets the increased counts of low-amplitude subsequent strokes in multiple-stroke flashes. At this point, two questions arise: (1) is the NLDN really detecting more small negative CG flashes, or (2) is the NLDN just misclassifying some negative cloud pulses as low-amplitude CG strokes? To answer these questions, we have attempted to determine the type of lightning that produced the small negative reports and whether the multiplicity of small negative flashes differs from negative flashes that have a larger I_p.

2. Experiment

2.1. Video Recording System

[6] Lightning flashes were recorded using a Canon GL1 digital video camera with 720 × 480 pixel resolution, operating at a standard rate of 30 video frames per second. Each video frame contained two interlaced fields, and the camera exposure time was set to 1/60 s (16.7 ms) to eliminate any dead time between fields. During the data analysis, each video frame was de-interlaced into two consecutive fields, and then these fields were converted back into images that could be viewed on a standard video monitor by interpolating between the horizontal scan lines. The result was an interpolated video record that had 60 images per second, one every 16.7 ms [*Parker and Krider*, 2003]. Strokes with an interstroke interval up to 33.4 ms may not be resolved by the video camera unless they follow a different path to ground.

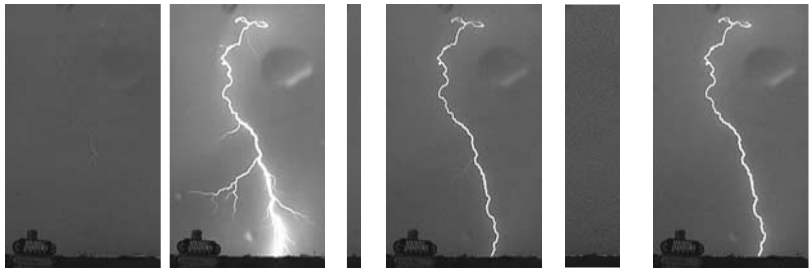
[7] To synchronize the video images to GPS time, each recording session began by recording a visual display of a GPS clock together with a blinking LED that was driven by a one-pulse-per-second GPS time signal. The LED marked a video field at the beginning of each second, and succeeding fields were counted forward (or backward) and synchronized to GPS time by adding (or subtracting) 16.7 ms for each field. Microsoft Excel was used to organize the times and images for each lightning event, and the images were time stamped using VirtualDub software (www.virtualdub.org) [*Parker and Krider*, 2003].

[8] Unfortunately, the LED time signal was not available for all recording sessions, and in cases when it was not, the video timing accuracy was limited to 83.3 ms because of an unpredictable drift in the internal clock frequency of the camera. All of the data recorded in TX-OK in 2003 and about 1/3 of the data recorded in AZ in 2003 had a timing accuracy of 83.3 ms, and all data recorded in 2004 had an accuracy of 16.7 ms.

[9] In this study, a ground stroke was regarded to have occurred within a particular video field if that field contained a clearly visible channel between the cloud and ground. The luminosity of most strokes ceased after one field, and all strokes that remained luminous for two or more fields were regarded as having a "continuing luminosity," even though in some cases there may have been a second stroke in the field that was not resolved by the video camera. Any subsequent increases in the continuing luminosity of the channel were regarded as M components [*Thottappillil et al.*, 1995] rather than a new stroke. If the channel contacted ground in more than one place in any single video field, it was usually considered to have two strokes; however, in cases where the channel forked close to the ground and the multiple contacts were likely to have been caused by multiple, upward connecting discharges attaching to the same leader, then that event was regarded as one stroke.

[10] Figure 1 shows the development of a six-stroke CG flash that contacted ground in one place and had a total duration of about 650 ms. It should be noted that in this case the NLDN only reported 4 of the 6 strokes; it missed the second and sixth strokes because they had peak amplitudes (or I_p values) that were below the nominal NLDN detection threshold (5 kA) [*Cummins et al.*, 2006] (see sections 2.2 and 3.2).

[11] The NLDN stroke DE is defined to be the percentage of all video strokes (first and subsequent) that were time correlated with a NLDN stroke report that was in a direction and at a range consistent with the video record. The NLDN flash DE is the percentage of video flashes that had at least one stroke at a time and direction that were coincident with a NLDN stroke report during that flash. When calculating the average values of I_p for negative flashes (first strokes), we excluded those few cases where the NLDN failed to detect the first stroke, as determined by video analysis. The average negative video multiplicity in each recording session is the total number of strokes detected on video (after subtracting all strokes that were associated with positive and bipolar flashes) divided by the total number of flashes detected on video (after subtracting all flashes that were bipolar or had a positive first stroke). This method of computing multiplicity implicitly assumes that all undetected



Field #	1	2	3	4 – 6	7 - 13	14
Interval	0 – 16 ms	17 – 33 ms	...	50 – 83.5 ms	…	216 – 233 ms
NLDN Time (UT)		23:42:47.542	...	No NLDN Report	…	23:42:47.762

Field #	15	16 - 26	27	28	29 - 38	39
Interval	…	250 – 267 ms	…	450 – 467 ms	…	633 – 650 ms
NLDN Time (UT)	…	23:42:47.801	…	23:42:47.991	…	No NLDN Report

Figure 1. Example of a six-stroke CG flash that was recorded in Arizona in 2003. The NLDN reported 4 of the 6 strokes (first, third, fourth, and fifth) in this flash. The I_p of the first stroke was −20.8 kA, and the estimated I_p for the second and sixth strokes (based on an E record) was −4.1 kA and −3.1 kA, respectively; both were below the nominal 5 kA detection threshold of the NLDN.

strokes are negative, and this assumption will be addressed further in section 4.1 to follow.

[12] We evaluated the DE of subsequent strokes that made a new ground contact and the DE of subsequent strokes that remained in a preexisting channel by manually viewing each flash and tabulating such information. In doing so, it was necessary to exclude some flashes because of ground obscuration or poor visibility that made it impossible to see the lowest portions of the channel and the number of ground contacts. All positive and bipolar flashes [*Rakov and Uman*, 2003, section 5] were also not included in this analysis.

2.2. Optical and Electric Field Waveforms

[13] In order to obtain subfield time resolution and other information about the lightning, we made an effort to record the waveforms produced by an optical sensor (O) and a broadband electric field antenna (E) in conjunction with the video data [*Parker and Krider*, 2003], but the O and E sensors were not available for most recording sessions. The circular field of view of the O sensor was centered in the camera field of view, and the O signal was capacitively coupled to eliminate the effects of any daylight background. The O output had a risetime of 2 μs or less and a 1/e decay time of 50 ms. The waveform digitizer was triggered on the output of the O sensor, and all waveforms were digitized at 500 kHz for a 1.0 s interval using a pretrigger delay of either 100 ms or 200 ms (see *Parker and Krider* [2003] for a more detailed description of the O and E sensors and the waveform digitizing system). These data allowed us to identify flashes that had two or more strokes in the same channel at intervals that were not resolved by the video camera and to determine correction factors for the measured stroke DE and negative multiplicity that compensated for the limited time resolution of the camera.

[14] The E waveforms also provided information about the type of lightning that triggered the NLDN, as well as a way to estimate the peak amplitude (I_p) of any stroke that was not detected by the NLDN, as long as it was preceded or followed by a detected stroke in the same channel. To a first approximation, the peak E that is radiated by a return stroke is proportional to the peak current [*Uman et al.*, 1975; *Schulz et al.*, 2005; *Jerauld et al.*, 2005]; therefore the peak current of any undetected stroke can be inferred simply by multiplying its peak field (obtained from the E waveform) by the ratio of the I_p for a detected stroke to the peak field of the detected stroke. This procedure assumes that there is no correlation between the stroke propagation speed and peak field [*Rakov*, 2004]. The statistical distributions of I_p values should be relatively immune to variations in the stroke propagation speed as long as these variations are random [*Rachidi et al.*, 2004].

2.3. Classification of Small, Single-Stroke NLDN Reports

[15] Given the time, location, and direction of viewing of each recording session, we searched the NLDN data set for all reports of small, single-stroke flashes (both positive and negative) that should have appeared within the camera field of view within a specified range interval. The corresponding video recordings were then examined to determine whether any channels to ground or other types luminous activity appeared at those times and in those directions. For inclusion in this analysis, the NLDN reports had to meet the following criteria: (1) positive polarity, $0 < I_p < 20$ kA; (2) negative polarity, $-10 < I_p < 0$ kA; (3) within ±15° of the center of the camera field of view; and (4) within a maximum range that will be discussed below.

[16] The last two criteria minimized the chances that a channel to ground would be outside the camera field of view because of a large NLDN location error or obscured by rainfall. The maximum range was different for each recording session, and in most cases was the largest distance that any flash was correlated with a NLDN report in the session, typically about 25 km. During this analysis, the video images were digitally enhanced as needed to increase the detection of very faint channels. These enhancements included changing the luminosity, chroma, contrast, hue, and saturation of the video image, and sometimes converting the image from color to black and white to increase the contrast and reduce the dark noise. Inverting the video image, i.e., changing the color of each pixel to its complimentary color, was also found to be useful when searching for very faint channels.

[17] After finding the video field that corresponded to the time of a NLDN report, the event was classified into one of three types, depending on the luminous activity that was observed: (1) CG, a visible channel between cloud and ground; (2) CB, a cloud brightening, i.e., there was evidence of cloud illumination or channels that did not contact ground; or (3) NL, no change in luminosity could be detected in that video field.

[18] For the CB and NL classifications, it is possible that a CG stroke did occur but was not detected on video because the channel was completely obscured, had insufficient luminosity, or was outside the camera field of view. Originally, we only searched the TX-OK data sets for small negative flashes because small NLDN reports were more numerous in that region; however, it soon became apparent that the poor visibility in TX-OK was biasing our results; therefore the analysis was expanded to include both AZ data sets. (The small positive NLDN reports in AZ were not analyzed because of the low numbers of such reports in that region.)

2.4. NLDN Data

[19] The NLDN data used in this study were provided by Vaisala, and were extracted from Vaisala's archive database. Only information related to individual stroke reports was used in order to facilitate the correlation between the NLDN and the video and waveform records. For each day with video observations, the status (up/down) of all sensors within 600 km of the video recording station was provided by Vaisala. For the TX-OK region in 2003 and 2004 and for the AZ region in 2003, there was no time when any of the nearest 7 sensors were not operational, thereby assuring nominal performance of the NLDN in those regions and time periods. For the AZ 2004 data set, however, the fourth closest sensor (about 400 km away) was not operating for six observation days (seven video sessions) in August. As we will see in section 3.1.2, this factor had a small but measurable effect on NLDN performance in southern Arizona during that period.

3. Results

[20] Section 3.1 summarizes the data obtained in each of the four measurement campaigns, and section 3.2 examines the subset of AZ data for which there were O and E measurements to determine the NLDN detection threshold and to correct the measured values of negative multiplicity. Section 3.3 evaluates the DE for different types of subsequent strokes, and section 3.4 compares the multiplicity and I_p distributions in AZ with those in TX-OK. The random NLDN location errors are discussed in section 3.5, and sections 3.6 and 3.7 examine the classification of small positive and small negative NLDN reports, respectively.

3.1. Experimental Campaigns

3.1.1. Arizona in 2003

[21] During the summer of 2003, about 19 hours of lightning activity were recorded in 18 different sessions near Tucson, AZ. Table 1 summarizes the dates and durations of each session together with the numbers of CG flashes and strokes that were recorded on video with a time accuracy of either ±83.3 ms or ±16.7 ms, together with the numbers (and percentages) of events that were detected by the NLDN. The average negative video multiplicity and the average values of I_p for all negative first strokes are given in the right two columns of Table 1. Altogether, 223 CG flashes containing at least 735 separate strokes were recorded with a time accuracy of 83.3 ms, and 448 CG flashes containing at least 1555 strokes were recorded with an accuracy of 16.7 ms. For data obtained with an accuracy of 83.3 ms, the average flash DE of the NLDN was 92% (205/223) and the measured stroke DE was 79% (578/735). For data obtained with 16.7 ms accuracy, the NLDN flash DE was 96% (431/448), and the measured stroke DE was 77% (1198/1555). If all data in Table 1 are combined, the average flash DE was 95% (636/671), and the measured stroke DE was 78% (1776/2290).

[22] The average multiplicity of negative flashes in Table 1 was 3.34 strokes per flash for video data obtained with a timing accuracy of 83.3 ms, and 3.52 for data obtained with an accuracy of 16.7 ms. The average negative video multiplicity of the combined data set was 3.46. There were 19 cases where the first stroke in the flash was not reported by the NLDN, but a subsequent stroke (usually the second) was reported, and none of these flashes have been included in the computation of the average I_p.

[23] The video timing accuracy was confirmed by producing histograms of the differences in the times reported by the NLDN and the times of the corresponding video fields for all correlated strokes in Table 1, and the results are shown in Figure 2. Events recorded with a 16.7 ms timing accuracy are shown in Figure 2a, and events recorded with an accuracy of 83.3 ms are shown in Figure 2b. A negative

Table 1. Summary of Measurements in Southern Arizona in 2003

Date	Recording Interval, min	Time Accuracy, ms	Video Flashes	Flashes Reported by NLDN Negative/Positive (Percentage)	Video Strokes	Strokes Reported by NLDN Negative/Positive (Percentage)	For Negative Flashes Only: Average Video Multiplicity	For Negative Flashes Only: Average I_p First Stroke,[a] kA
30 May	31	83.3	6	4/1 (83.5)	13	11/1 (92)	2.40	−19.3
30 May	55	83.3	19	17/0 (90)	56	39/0 (70)	2.95	−14.7
12 July	31	83.3	36	34/0 (94)	148	125/0 (85)	4.11	−19.9
12 July	31	16.7	5	2/2 (80)	19	13/2 (79)	5.67	
13 July	189	83.3	9	2/3 (56)	12	3/3 (50)	1.50	−11.6
13 July	189	16.7	3	1/1 (67)	4	1/1 (50)	1.50	
15 July	95	83.3	69	65/0 (94)	204	164/0 (80)	2.96	−19.5
15 July	95	16.7	24	23/0 (96)	68	48/0 (71)	2.83	
15 July	90	83.3	8	8/0 (100)	14	10/0 (71)	1.75	−21.3
15 July	90	16.7	44	41/0 (93)	113	83.3/0 (74)	2.57	
21 July	132	83.3	32	29/0 (91)	113	83.3/0 (74)	3.53	−15.7
21 July	132	16.7	92	89/1 (98)	310	244/1 (79)	3.40	
23 July	78	83.3	2	2/0 (100)	4	4/0 (100)	2.00	−16.2
23 July	78	16.7	19	19/0 (100)	53	45/0 (85)	2.79	
24 July	20	83.3	14	13/0 (93)	57	45/0 (79)	4.07	−16.0
24 July	20	16.7	10	9/0 (90)	32	24/0 (75)	3.20	
25 July	23	83.3	6	5/0 (83)	23	14/0 (61)	3.83	−40.4
25 July	23	16.7	1	1/0 (100)	1	1/0 (100)	1.00	
27 July	84	83.3	12	12/0 (100)	53	40/0 (76)	4.42	−22.8
27 July	84	16.7	66	64/0 (97)	287	209/0 (73)	4.35	
9 August	14	83.3	2	2/0 (100)	2	2/0 (100)	1.00	−11.2
14 August	78	83.3	4	4/0 (100)	22	19/0 (86)	5.50	−19.5
14 August	78	16.7	36	29/4 (92)	109	83/4 (80)	3.28	
18 August	47	16.7	28	28/0 (100)	106	92/0 (87)	3.79	−28.4
22 August	84	16.7	86	84/0 (98)	322	254/0 (79)	3.74	−17.5
23 August	58	83.3	3	3/0 (100)	10	10/0 (100)	3.33	−19.9
23 August	58	16.7	30	30/0 (100)	116	80/0 (69)	3.87	
25 August	10	16.7	3	2/0 (67)	10	8/0 (80)	3.33	−30.2
26 August	6	83.3	1	1/0 (100)	4	4/0 (100)	4.00	−23.60
26 August	6	16.7	1	1/0 (100)	5	4/0 (80)	5.00	
All data		83.3	223	201/4 (92)	735	574/4 (79)	3.34	
All data		16.7	448	421/8 (96)	1555	1190/8 (77)	3.52	

[a]Values of average first stroke I_p are for both 16.7 ms and 83.3 ms time accuracy data.

difference means the time reported by the NLDN was before the video field. For all strokes that had 16.7 ms timing accuracy, the most frequent difference was between 0 and 4 ms, and for strokes recorded with 83.3 ms accuracy, the most frequent difference was between −4 and −8 ms, and in both cases the relative percentage of events is low at the boundaries of the coincidence windows.

3.1.2. Arizona in 2004

[24] About 8 hours of lightning activity were recorded in southern AZ in 2004 in 10 different sessions, and the results are summarized in Table 2. A total of 426 CG flashes containing at least 1330 strokes were recorded on video, all with a timing accuracy of 16.7 ms. The NLDN flash DE was 91% (388/426), and the measured stroke DE was 73% (970/1330). The average video multiplicity of negative flashes was 3.16 strokes per flash. There were 22 multiple-stroke flashes recorded on video where the first stroke was not reported by the NLDN, and there were 2 additional flashes (with multiplicities of 5 and 6) that were not reported until the third stroke. One bipolar flash, with four strokes and three contact points, had its first stroke correlated with a negative NLDN report; the second stroke was not correlated with an NLDN report; and the third and fourth strokes were correlated with positive NLDN reports.

[25] In order to evaluate the effect of the missing NLDN sensor in August 2004 (see section 2.4), the DE was computed separately for the 3 sessions in July 2004 and the 7 sessions in August. The average flash DE for the 171 flashes recorded in July 2004 was 95.5% and was consistent with observations in AZ 2003. The average flash DE for the 255 flashes recorded in August 2004 was only 89.6%; therefore the missing sensor caused a small but measurable reduction in NLDN performance during this period.

3.1.3. Texas and Oklahoma in 2003

[26] During April 2003, about 5 hours of lightning activity were recorded in 3 different sessions in north Texas and southern Oklahoma between Dallas and Oklahoma City (TX-OK), all with a timing accuracy of 16.7 ms. The results are summarized in Table 3. The NLDN flash DE was 81% (48/59), the measured stroke DE was 75% (95/126), and the average negative video multiplicity was 2.20 strokes per flash. Two CG flashes were not detected until the second stroke in the flash. Note in Table 3 that the number of flashes recorded in each session was only 25 or less, and that the storm on 24 April 2003 had a very low flash DE (68%), and a very low video multiplicity (1.53 strokes per flash). We believe that the combination of these factors has biased our estimates of the true NLDN DE in TX-OK in 2003, and this issue will be addressed further in section 4.1.

3.1.4. Texas and Oklahoma in 2004

[27] During April of 2004, about 12 hours of lightning activity were recorded in TX-OK in 8 different sessions, and the results are summarized in Table 4. The NLDN flash DE was 94% (291/308), the measured stroke DE was 87% (660/756), and the average video multiplicity of negative flashes was 2.59 strokes per flash. 14 CG flashes were not detected

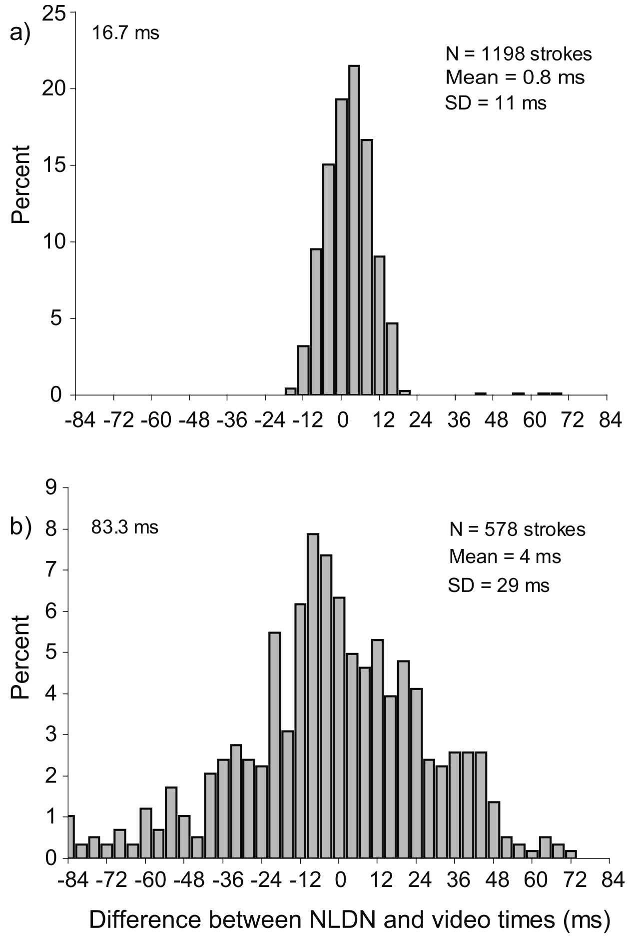


Figure 2. Time differences between the NLDN events and the corresponding video fields in AZ with (a) 16.7 ms accuracy and (b) 83.3 ms accuracy.

until the second stroke in the flash; one five-stroke flash was not detected until the third stroke; and two three-stroke flashes were not detected until the third stroke. One bipolar flash was recorded on video, and this event had 5 strokes with 4 separate ground contacts; the first four strokes were correlated with negative NLDN reports, and the fifth was correlated with a positive report.

3.2. Optical and Electric Field Measurements in Arizona in 2003

[28] Of the 671 flashes (containing 2290 strokes) that were recorded on video in AZ in 2003, 157 had correlated O waveforms, and 91 had correlated O and E waveforms. One of the 91 was the multiple-stroke flash shown in Figure 1 that contained 6 strokes; 4 were correlated with NLDN reports and 2 were not. In this case, we could infer the peak current of the strokes that were not reported by the NLDN by comparing the peak amplitude of the electric field (E) that was radiated by these strokes with the amplitudes of strokes that were reported by the NLDN, as discussed in section 2.2. This analysis shows that if the I_p of the first stroke was −20.8 kA, as reported by the NLDN, then the values of I_p for the 2nd and 6th strokes were only −4.1 kA and −3.1 kA, respectively, and as we will see in the next paragraph, both were below the nominal 5 kA detection threshold of the NLDN in southern Arizona.

[29] Within the 91 video flashes (containing 310 strokes) that had correlated O and E records, 38 contained strokes that were not reported by the NLDN where the value of I_p could be inferred in the above fashion. Figure 3 summarizes the values of $|I_p|$ for 134 negative strokes (in the 38 flashes) that were reported by the NLDN and also for 64 strokes that were not reported. Note that for these 38 flashes, the NLDN did not report any stroke with an $|I_p| \leq 5$ kA; therefore we infer that 5 kA is a reasonable lower bound for the NLDN detection threshold in southern Arizona.

[30] The O and E waveforms have also been analyzed to determine the number of subsequent strokes that were not resolved by the video camera because of the finite integration time (16.7 ms) of each video field. Figure 4 compares the negative flash multiplicities and stroke counts that were measured using the video data set, the O and E recordings, and the NLDN for the 91 flashes that had correlated O and E waveforms. The video camera recorded all 91 first strokes, but because of its inherently lower time resolution, it failed to resolve about 13% (34/253) of the subsequent

Table 2. Summary of Measurements in Southern Arizona in 2004

Date	Recording Interval, min	Video Flashes	Flashes Reported by NLDN Negative/Positive (Percentage)	Video Strokes	Strokes Reported by NLDN Negative/Positive (Percentage)	For Negative Flashes Only: Average Video Multiplicity	For Negative Flashes Only: Average I_p First Stroke, kA
12 July	52	15	14/0 (93)	56	53/0 (95)	3.73	−20.1
12 July	61	26	23/0 (89)	72	46/0 (64)	2.77	−15.9
13 July	52	130	124/2 (97)	357	293/2 (83)	2.77	−23.0
9 August	47	15	9/0 (60)	42	21/0 (50)	2.80	−18.6
10 August	23	2	1/0 (50)	3	2/0 (67)	1.50	−13.9
12 August	34	55	47/0 (86)	173	104/2[a] (61)	3.13[b]	−12.9
12 August	51	52	44/0 (85)	140	82/0 (59)	2.69	−17.8
12 August	37	11	10/0 (91)	23	18/0 (78)	2.09	−16.2
13 August	61	9	4/4 (89)	16	12/0 (75)	2.40	−44.3
14 August	58	111	105/1 (96)	448	334/1 (75)	4.06	−23.6
All data		426	381/7 (91)	1330	961/9 (73)	3.16[c]	

[a]The third and fourth strokes of a four-stroke flash were of positive polarity.
[b]This recording session had 1 bipolar flash with 4 strokes, 2 of which were positive, 1 was negative, and 1 was not detected. This flash has not been included in the multiplicity calculation, i.e., 169/54 = 3.13.
[c]The calculation of the average negative video multiplicity does not include the bipolar flash in the session on 12 August, i.e., 1319/418 = 3.16 (see footnote b).

Table 3. Summary of Measurements in Northern Texas and Southern Oklahoma in 2003

Date	Recording Interval, min	Video Flashes	Flashes Reported by NLDN Negative/Positive (Percentage)	Video Strokes	Strokes Reported by NLDN Negative/Positive (Percentage)	For Negative Flashes Only: Average Video Multiplicity	For Negative Flashes Only: Average I_p First Stroke, kA
16 April	81	25	21/1 (88)	68	53/1 (79)	2.79	−11.0
20 April	138	15	13/0 (87)	30	23/0 (77)	2.00	−14.2
24 April	91	19	11/2 (68)	28	16/2 (64)	1.53	−17.0
All Data		59	45/3 (81)	126	92/3 (75)	2.20	

strokes that were detected by the O and E sensors. On the basis of the table in Figure 4, we infer that the NLDN missed about 28% (72/253) of the subsequent strokes, and this implies that the NLDN DE for subsequent strokes is actually only about 72% (181/253) rather than the 83% (181/219) that was measured for this (limited) video data set. The comparisons in Figure 4 show that the video-based, measured stroke DEs (first plus subsequent), are overestimates and that the actual multiplicities are about 89% of the measured values.

[31] Of the 91 video flashes that had correlated O and E records, only three were not detected by the NLDN; of these, two were single-stroke flashes, and one was a three-stroke flash. The peak currents for these strokes could not be inferred, however, because there were no NLDN reports available for comparison.

3.3. NLDN Detection Efficiency Versus Stroke Type

[32] Table 5 summarizes the video- and NLDN-based DE values for negative first strokes, the subsequent strokes that produced a new ground contact, and the subsequent strokes that remained in a preexisting channel for each measurement campaign. As noted in section 2.1, the flash and stroke counts in this analysis are slightly smaller than those shown in Tables 1–4 because of ground obscuration, poor visibility, and the exclusion of positive and bipolar flashes. In the AZ 2003 campaign, the DE for first strokes (95%) was about 14% higher than the DE for subsequent strokes that created a new ground contact (81%), which in turn was about 13% higher than the (uncorrected) DE for subsequent strokes that remained in a preexisting channel (68%). Therefore the DE for first strokes was about 27% higher than the DE for subsequent strokes that remained in a preexisting channel. In the AZ 2004 campaign, the first stroke DE (92%) was about 14% higher than the DE for subsequent strokes that created a new ground contact (78%), and the latter DE was about 17% higher than the (uncorrected) DE for the subsequent strokes remaining in a preexisting channel (61%). Again, the DE for first strokes was about 30% higher than the DE for subsequent strokes that remained in a preexisting channel.

[33] In the TX-OK 2004 campaign, the first stroke DE (87%) was only about 7% higher than the DE for subsequent strokes that created a new ground contact (80%), and there was no significant difference in the measured DE for the subsequent strokes that remained in a preexisting channel from strokes that created a new ground contact. In the TX-OK 2003 campaign, the DE for subsequent strokes that created a new ground contact (83.5%) was actually higher than the value for first strokes (79%), although the first stroke DE was higher than the DE for subsequent strokes remaining in a preexisting channel (75%).

3.4. Regional Comparisons

[34] Table 5 shows that the DE for negative first strokes in TX-OK in April (79% in 2003 and 87% in 2004) was systematically lower than the DE for negative first strokes throughout the summer in AZ (95% in 2003 and 92% in 2004), but the mean values of I_p (for first strokes) in the campaigns with large data sets (AZ 2003–2004 and TX-OK 2004) were very similar. Clearly, if the lightning characteristics were the same in both regions, we would expect to have a higher first stroke DE in TX-OK because there are more NLDN sensors per unit area in that region and because it is in the interior of the network. The fact that the DE for first strokes is lower in TX-OK can be explained by examining the distributions of $|I_p|$ for negative first strokes in TX-OK 2004 and AZ 2004 shown in Figure 5. Note that the TX-OK distribution is broader and that there are larger

Table 4. Summary of Measurements in Northern Texas and Southern Oklahoma in 2004

Date	Recording Interval, min	Video Flashes	Flashes Reported by NLDN Negative/Positive (Percentage)	Video Strokes	Strokes Reported by NLDN Negative/Positive (Percentage)	For Negative Flashes Only: Average Video Multiplicity	For Negative Flashes Only: Average I_p First Stroke, kA
21 April[a]	155	52	51/0 (98)	135	115/1 (86)	2.55	−39.7
21 April	24	29	24/1 (86)	49	40/1 (84)	1.71	−12.7
22 April	5	1	1/0 (100)	4	4/0 (100)	4.00	−32.2
22 April	138	25	24/0 (96)	77	73/0 (95)	3.08	−17.5
22 April	87	66	63/0 (96)	198	173/0 (87)	3.00	−14.3
23 April	190	95	81/9 (95)	221	181/9 (86)	2.47	−16.1
23 April[b]	87	15	0/12 (80)	15	0/12 (80)	1.00	37.8
24 April	10	25	25/0 (100)	57	51/0 (90)	2.28	−24.7
All Data		308	266/25 (94.5)	756	634/26 (87)	2.57[c]	

[a]This recording session had 1 bipolar flash with 5 strokes. The fifth stroke was correlated to a positive NLDN report. This flash is not included in the multiplicity calculation, i.e., 130/51 = 2.55.

[b]All 15 video flashes in this session were single-stroke, and the 12 correlated flashes were of positive polarity.

[c]The calculation of the overall average does not include the positive polarity storm on 23 April or the bipolar flash on 21 April, i.e., 726/282 = 2.57.

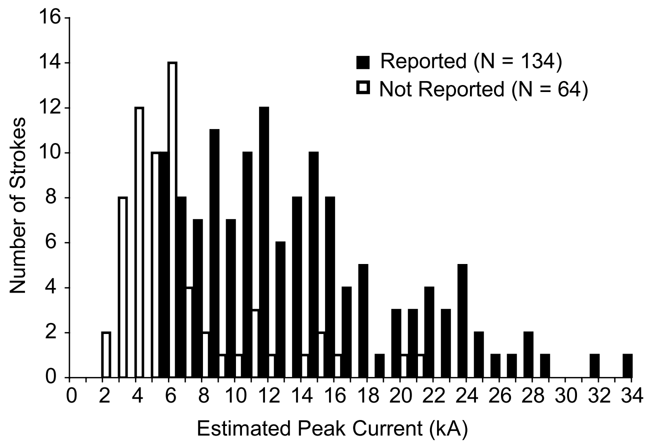


Figure 3. Estimated peak current, I_p, of negative strokes that were reported by the NLDN (solid bars) and the inferred I_p of strokes that were not reported (open bars) from data acquired in southern Arizona in 2003. Note the absence of any reported strokes with an $|I_p| \leq 5$ kA. Note also that 32 (50%) of the strokes that were not reported had an $|I_p| <$ 5 kA.

percentages of events that have both lower and higher values of $|I_p|$ than in AZ. The AZ distribution has a larger percentage of $|I_p|$ values in the intermediate range (10 to 40 kA). This difference is reflected in the median values of I_p and the standard deviations in Table 5: −18.1 kA and 10.8 kA, respectively, for first strokes in AZ 2004 and −14.3 kA and 19.1 kA for first strokes in TX-OK 2004. Thus the first stroke DE in TX-OK was lower simply because there was a higher percentage of low-amplitude first strokes in that region than in AZ. The mean values of I_p in both regions are similar because the larger number of low-amplitude first strokes in TX-OK is offset by 9 (3.6%) negative first strokes that had an $|I_p| > 70$ kA (see Figure 5), including three values between 100 and 153 kA. The largest negative first stroke in the AZ 2004 data set had an $|I_p|$ of only 69.4 kA.

[35] Table 5 shows that in AZ (2003 and 2004), the difference in the average I_p between negative first strokes and the subsequent strokes that remained in a preexisting channel was 7 to 8 kA, and this produced about a 30% difference in the measured DEs. The corresponding difference in I_p in TX-OK 2004 was about 9 kA, but the corresponding difference in the stroke DE was only 6%. We have examined the distributions of I_p for subsequent strokes in TX-OK 2004 and AZ 2004, and find no substantial differences; the similarity is confirmed by the similar mean and median values of I_p for subsequent strokes in both regions (see Table 5). Therefore we attribute the higher DE for subsequent strokes in TX-OK to the higher area density of sensors in that region, and the fact that this region is in the interior of the network with sensors in all directions. The measurements in AZ were near the southern edge of the NLDN where the area density of sensors is low and their locations are primarily to the north. We note that the overall characteristics of lightning in TX-OK may not be well represented by our limited samples of lightning in the month of April.

[36] Figure 6 shows the video multiplicities of negative flashes in AZ (Figure 6a) and TX-OK (Figure 6b) for the combined 2003 and 2004 data sets. The distributions have been plotted separately for flashes that had both small ($|I_p| \leq 10$ kA) and large ($|I_p| > 10$ kA) amplitude first strokes, and it should be noted that 52% of the small flashes in TX-OK had a multiplicity of 1, and only 33% of the large flashes had a multiplicity of 1. The results in AZ are similar; 45% of the flashes with small first strokes had a multiplicity of 1, and only 28% of the large flashes had a multiplicity of 1. The distributions in Figure 6 are consistent with the hypothesis posed in our Introduction that the observed postupgrade decreases in the NLDN multiplicity in some regions are due, at least in part, to the detection of more small, single-stroke flashes.

[37] There were 23 video flashes that were correlated with positive NLDN reports in AZ in 2003 and 2004; 20 flashes were single-stroke and 3 flashes contained 2 strokes. For each of the two-stroke positive flashes, the second stroke created a new ground contact and was not reported by the NLDN. If each of the video subsequent strokes was also positive, the average multiplicity of positive flashes in AZ was 1.13. There were 24 video flashes correlated with positive NLDN reports in TX-OK in 2003 and 2004, and 23 of these were single stroke. One was a two-stroke flash, with the second stroke remaining in the same channel, but the second stroke was not reported by the NLDN. Again, if the second stroke was positive, then the average multiplicity of positive flashes in TX-OK was 1.04.

3.5. NLDN Position Differences of Strokes in the Same Channel

[38] For the negative flashes that showed multiple strokes in the same channel on video, a measure of the random NLDN position error can be obtained by examining the 2-D position differences of the corresponding NLDN stroke locations. This analysis was done for all subsequent strokes that were reported by the NLDN and remained in the same channel as the first stroke. Figure 7 shows distributions of the differences in the subsequent stroke positions from the first stroke for the AZ 2003 and TX-OK 2004 data sets. The differences shown in Figure 7 have been computed from the measured position errors by scaling them by $1/\sqrt{2}$. This

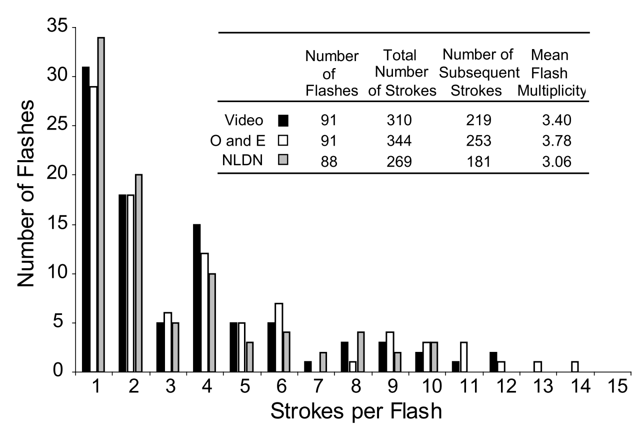


Figure 4. Flash multiplicities for the 91 flashes obtained in southern Arizona in 2003 using the video camera, the optical (O) and electric field (E) sensors, and the NLDN.

Table 5. DE, Average, and Median Values of I_p for Negative First Strokes, Subsequent Strokes That Produced New Ground Contacts, and Subsequent Strokes That Remained in a Preexisting Channel

	Number of Strokes on Video	Number of Strokes Reported by the NLDN	Detection Efficiency, %	Average I_p, kA	Median I_p, kA	Standard Deviation, kA
		Arizona 2003				
First strokes	632	602	95	−19.3	−16.5	10.3
Subsequent strokes with new ground contacts	277	225	81	−15.0	−15.9	6.7
Subsequent strokes in a preexisting channel	1302	886	68	−11.6	−12.4	8.1
		Arizona 2004				
First strokes	380	351	92	−20.5	−18.1	10.8
Subsequent strokes with new ground contacts	167	130	78	−16.9	−16.5	7.2
Subsequent strokes in a preexisting channel	592	361	61	−13.2	−14.0	9.1
		Texas and Oklahoma 2003				
First strokes	52	41	79	−14.6	−13.3	8.7
Subsequent strokes with new ground contacts	12	10	83.5	−12.6	−18.6	10.1
Subsequent strokes in a preexisting channel	47	35	75	−11.9	−12.1	6.2
		Texas and Oklahoma 2004				
First strokes	266	232	87	−20.4	−14.3	19.1
Subsequent strokes with new ground contacts	114	91	80	−14.1	−13.8	8.6
Subsequent strokes in a preexisting channel	291	235	81	−11.5	−11.9	8.3

scaling is necessary because both position calculations are subject to random errors. Assuming that the random errors for each measurement are uncorrelated and equal, the RMS position error between both locations will be $\sqrt{2}$ larger than the RMS error of either measurement taken alone. Because there is a possibility that the channel geometry and/or the actual ground contact varied slightly from stroke to stroke and were not resolved by the video camera, the differences in Figure 7 should be regarded as upper bounds on the actual random NLDN position differences. The dashed lines in Figure 7 show the average lengths of the semimajor axes (SMA) of the 10%, 50%, and 90% confidence ellipses (provided by the NLDN for each event) for the strokes that appear in Figure 7 (see *Cummins et al.* [1998] for a discussion of SMA). Note that the random position differences are well within the boundaries defined by the 10% and 90% SMA distributions, and that the measured differences are below the median (50%) SMA curve more than half the

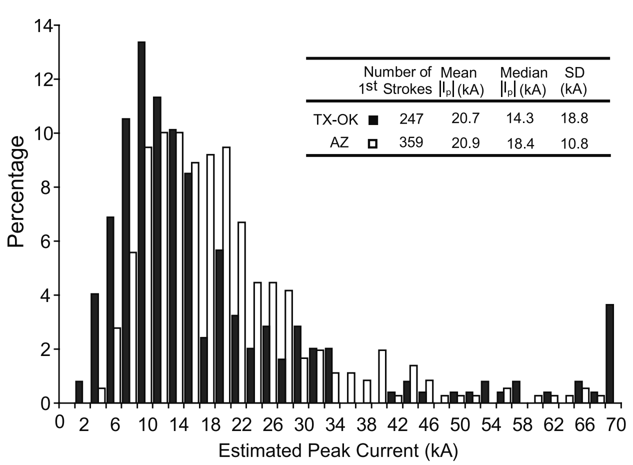


Figure 5. Distributions of I_p values for all negative first strokes in AZ (open bars) and in TX-OK (solid bars) in 2004. Nine first strokes had an $|I_p|$ greater than 70 kA, and two had negative values between 2 kA and 4 kA.

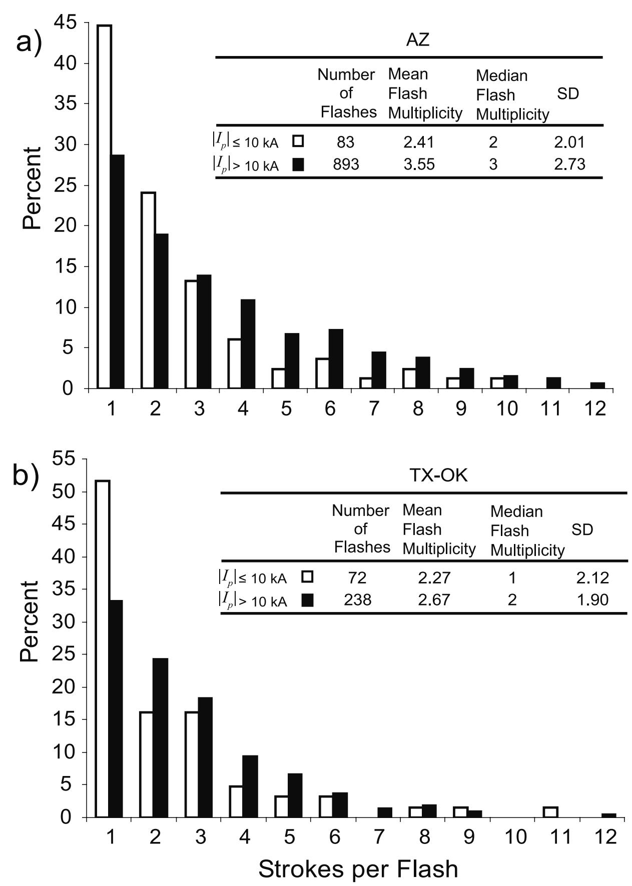


Figure 6. Distributions of the measured video multiplicities of negative flashes in (a) AZ and (b) TX-OK in 2003 and 2004 for both low-amplitude and high-amplitude events. Note that 52% of the flashes in TX-OK with $|I_p| \leq 10$ kA were single stroke and that there are more high-multiplicity flashes in AZ than in TX-OK.

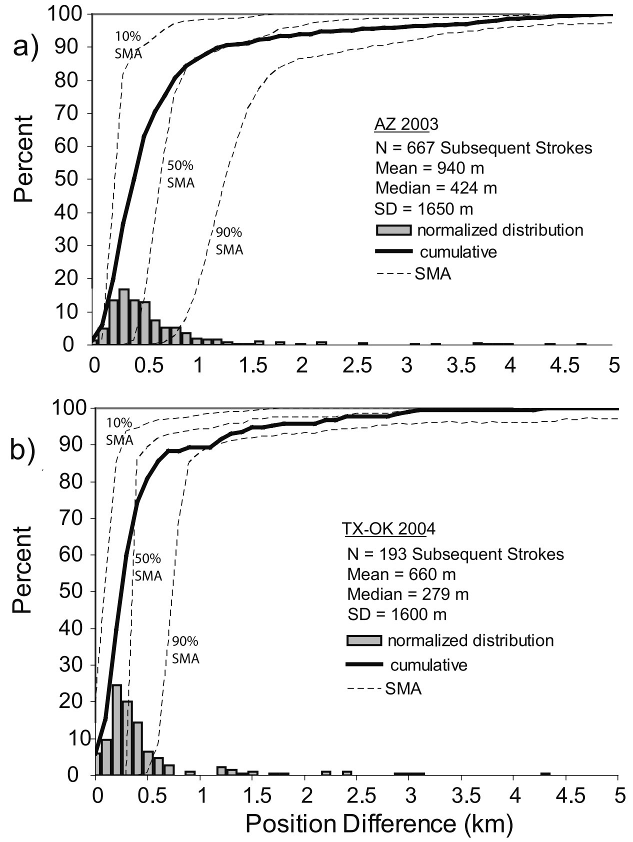


Figure 7. NLDN position differences for subsequent strokes that remain in the same channel as the first stroke in (a) AZ 2003 and (b) TX-OK 2004. The dashed lines are, from left to right, the modeled 10%, 50%, and 90% SMA curves for the NLDN in the respective regions, which were provided by Vaisala.

time. The mean and median location differences in Figure 7 are 660 m and 279 m, respectively in TX-OK 2004 and 940 m and 424 m in AZ 2003. These values are smaller than the NLDN location accuracies posited by *Cummins et al.* [1998] and measurements of rocket triggered lightning in Florida [*Jerauld et al.*, 2005], but they do not include the effects of any residual systematic (or nonrandom) errors in the NLDN locations.

3.6. Classification of Small Positive NLDN Reports in TX-OK

[39] During analyses of the TX-OK data set, it became clear that there is no unique value of I_p above which all positive NLDN reports can be regarded as true CG strokes or flashes; therefore the classifications of small positive NLDN reports have been divided into four ranges of I_p, and Table 6 shows the results for each amplitude range.

[40] There were 420 positive NLDN reports with an $I_p \leq 10$ kA, and only 1.4% (6/420) were confirmed to be CG strokes on video. Cloud brightening or enhanced cloud illumination was observed for 80 reports, and 334 reports showed no evidence of luminous activity on the video records. On the basis of our experience in analyzing the luminous development of CG flashes, we believe it is unlikely that a CG stroke would produce illumination within or above the cloud base and not below; therefore we think the video recordings of cloud brightening are very likely cloud discharges. However, for the NLDN reports that did not show any luminous activity at all, it is possible that there was a CG stroke, but the channel was either physically obscured, its luminosity was below the detection threshold of the video camera, or the stroke was outside the field of view of the camera due to one or both of the following: (1) the camera viewing direction was inaccurately measured or (2) the stroke location was outside the 50% SMA distance reported by the NLDN. If we exclude all NLDN reports that showed no luminous activity from the statistics, then only 7% (6/86) of the small positive NLDN reports with $I_p \leq 10$ kA were CG strokes, and this clearly represents an upper bound on the true value.

[41] Of the 81 positive NLDN reports that had an I_p in the range 10 kA < $I_p \leq 15$ kA, 3 were CG strokes, 7 showed cloud brightening, and 71 showed no luminous activity at all. Thus the fraction of NLDN reports in this amplitude range that were CG strokes was at least 3.7% (3/81), and if the reports that showed no luminous activity are excluded, the percentage was 30% (3/10). There were 28 positive reports with an I_p in the range 15 kA < $I_p \leq 20$ kA, and of these, 2 were CG strokes, 7 showed cloud brightening, and 16 showed no luminous activity at all. Thus the percentage of positive reports that were CGs was at least 8% (2/25), and if the reports showing no luminous activity are excluded, the percentage was 22% (2/9). There were 45 positive NLDN reports with an I_p > 20 kA, and the video data show that 30 of these were CG strokes; 2 produced cloud illumination; and 13 showed no luminous activity at all. Thus we can conclude that when the I_p is greater than 20 kA, at least 67% (30/45) of the positive NLDN reports are CG strokes, and if the reports with no luminous activity are excluded, the fraction rises to 94% (30/32); again, this is likely an upper bound on the true value.

3.7. Classification of Small Negative NLDN Stroke Reports

[42] The classification of small negative NLDN reports (-10 kA $\leq I_p < 0$ kA) was examined for all such events in our data set. For this evaluation, the video records from 2004 have also been divided into "day" and "night" categories in order to determine whether there was a detection bias because of the difficulty of detecting very faint channels in the daytime records. Table 7 summarizes the results for the AZ campaigns in 2003 and 2004. There were 40 small negative NLDN reports in AZ 2003, and of these, 55% (22/40) showed clear channels to ground. Eight of the 22 events that the NLDN classified as low-amplitude,

Table 6. Classification of Small Positive NLDN Reports in TX-OK[a]

I_p Categories, kA	CG	CB	NL	Total Count
$0 < I_p \leq 10$	6	80	334	420
$10 < I_p \leq 15$	3	7	71	81
$15 < I_p \leq 20$	2	7	16	25
$I_p > 20$	30	2	13	45
Total	41	96	434	574

[a]CG, a channel between cloud and ground was observed; CB, cloud illumination or channels aloft were observed; NL, no luminous activity was detected.

Table 7. Classification of Small ($|I_p| \leq 10$ kA), Single-Stroke, Negative NLDN Flash Reports in AZ[a]

Data Set	Night or Day	CG	CB	NL	Total NLDN	Total Video CG (Percentage)
AZ 2003	night	22[b]	4[c]	14	40	22 (55)
AZ 2004	night	8	2	0	10	8 (80)
AZ 2004	day	12[d]	0	18[e]	30	12 (40)
Total day		12	0	18	30	12 (40)
Total night		30	6	14	50	30 (60)

[a]CG, A channel between cloud and ground was observed; CB, cloud illumination or channels aloft were observed; NL, no luminous activity was detected.

[b]Eight of the 22 single-stroke NLDN reports were multiple-stroke flashes on video.

[c]One CB event showed a horizontal channel near the cloud base that propagated outside of the field of view and was subsequently reilluminated three times.

[d]Three of the 12 single-stroke NLDN reports were multiple-stroke flashes on video.

[e]Eighteen NL events came from a distant storm that was near the maximum range of detectability.

single-stroke flashes were actually flashes that contained 2 to 3 strokes. Of the 18 small negative reports that did not show a channel to ground on video, 14 showed no luminous activity, 3 showed cloud brightening, and 1 showed a clear channel near the cloud edge but not to ground (a CB). There were no daytime recordings in the AZ 2003 campaign.

[43] The AZ 2004 data set contained 40 small negative NLDN reports (see Table 7), 10 at night and 30 in the daytime. 50% (20/40) of the AZ 2004 video records showed clear channels to ground, and 3 (of the 20) were multiple-stroke flashes. There were 18 NLDN reports that showed no luminous activity, and all of these were in the daytime near the maximum range of detection on video. Two of the 10 night reports in AZ 2004 showed cloud brightening. If all small negative NLDN reports in AZ are combined, then 52% (42/80) showed clear channels to ground, 7.5% (6/80) showed cloud brightening or a channel near the cloud base, and 40% (32/80) showed no luminous activity at all. Note that 60% of the daytime reports had no luminosity, but only 36% of the nighttime reports had no luminosity.

[44] Table 8 shows that there were 6 negative NLDN reports with $|I_p| \leq 10$ kA in the TX-OK 2003 data set; 4 were single-stroke CG flashes, 1 showed cloud brightening, and 1 showed no luminous activity. Thus 67% (4/6) of the small negative reports in that campaign were confirmed to be CG strokes. The TX-OK 2004 data set contained 18 small negative reports, 7 were recorded at night, and 11 were recorded in the daytime. 33% (6/18) of the TX-OK 2004 reports were CGs, and one report showed cloud brightening. None of the small negative NLDN reports in TX-OK were produced by a multiple-stroke flash. Note that 82% of the daytime reports showed no luminous activity, and only 23% of the nighttime reports showed no luminosity.

[45] If all data in Tables 7 and 8 are combined, we can conclude that at least 50% (52/104) of the small negative NLDN reports were classified correctly as CGs. It should be noted that 66% (27/41) of the combined daytime reports showed no luminosity, whereas only 27% (17/63) of the combined nighttime reports showed no luminosity. Also, 18 of the 32 NL events in Table 7 occurred during one daytime storm at a range that was near the limit of detectability. These results show that there is a clear day/night bias on low peak current events. If we exclude all the NL events from the statistics because of the detection bias, then a reasonable upper bound on the percentage of the small negative NLDN reports that were classified correctly is 87% (52/60).

3.8. Luminous Characteristics of Small Negative Flashes

[46] In our analyses of the video records of small negative flashes, it appeared that many of these flashes had long leader durations (or slow vertical leader velocities) and considerable horizontal development relative to flashes that had a larger $|I_p|$. Several low $|I_p|$ events were strokes to ground that developed from a previously established, horizontal discharge propagating along or near the cloud base, and many low $|I_p|$ events exhibited large, abrupt changes in the direction of propagation. A large fraction of the low I_p events also contained a continuing luminosity and M components.

[47] To illustrate these characteristics, Figures 8–10 show three examples of small negative flashes. The single-stroke flash in Figure 8 (I_p = −7.6 kA) developed from a horizontal air discharge and was associated with an abrupt change in the direction of propagation. The single-stroke flash in Figure 9 (I_p = −5.0 kA) had extensive horizontal development and a continuing luminosity that persisted for about 300 ms. Figure 10 shows the development of the smallest, negative NLDN report (I_p = −2.8 kA) in the data set that was probably a CG flash. It began as an air discharge that propagated in two different directions for 50 to 67 ms. After 67 ms, the CG stroke developed from the air discharge and persisted for at least 318 ms. Two pulsations in the continuing luminosity occurred (that were likely M components), and the channels that were initially air discharges persisted for about 170 ms.

4. Discussion

4.1. Flash and Stroke Detection Efficiencies and Multiplicities

[48] Video recordings that are synchronized to GPS time provide an independent way to assess the NLDN flash and stroke detection efficiency and to estimate the random NLDN position errors. As noted in section 2.1, the limited time resolution (16.7 ms) of the video camera has prevented us from resolving strokes that had an interstroke interval up to 33.4 ms. In section 3.2, we used analyses of the O and E waveforms produced by 91 flashes in AZ to derive

Table 8. Classification of Small ($|I_p| \leq 10$ kA), Single-Stroke, Negative NLDN Flash Reports in TX-OK[a]

Data Set	Night or Day	CG	CB	NL	Total NLDN	Total Video CG (Percentage)
TX-OK 2003	night	14[b]	1	1	6	4 (67)
TX-OK 2004	night	4	1	2	7	4 (57)
TX-OK 2004	day	2	0	9	11	2 (18)
Total day		2	0	9	11	2 (18)
Total night		8	2	3	13	8 (62)

[a]CG, a channel between cloud and ground was observed; CB, cloud illumination or channels aloft were observed; NL, no luminous activity was detected.

[b]Ten of the 14 single-stroke NLDN reports were multiple-stroke flashes on video.

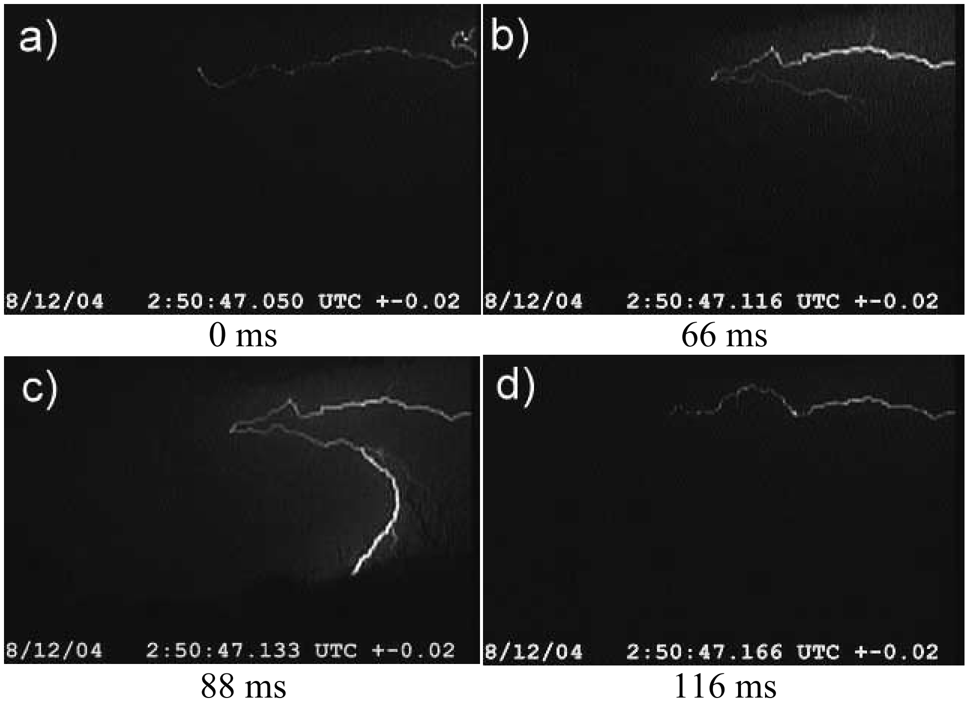


Figure 8. (a–d) Sequence of video fields showing the luminous development of a small negative CG flash with an $I_p = -7.6$ kA. In Figure 8a an air discharge begins and continues into Figure 8b. Figure 8c shows the CG stroke, and Figure 8d shows how the air discharge persisted after the CG stroke. This particular flash did not produce a continuing luminosity longer than 16.7 ms.

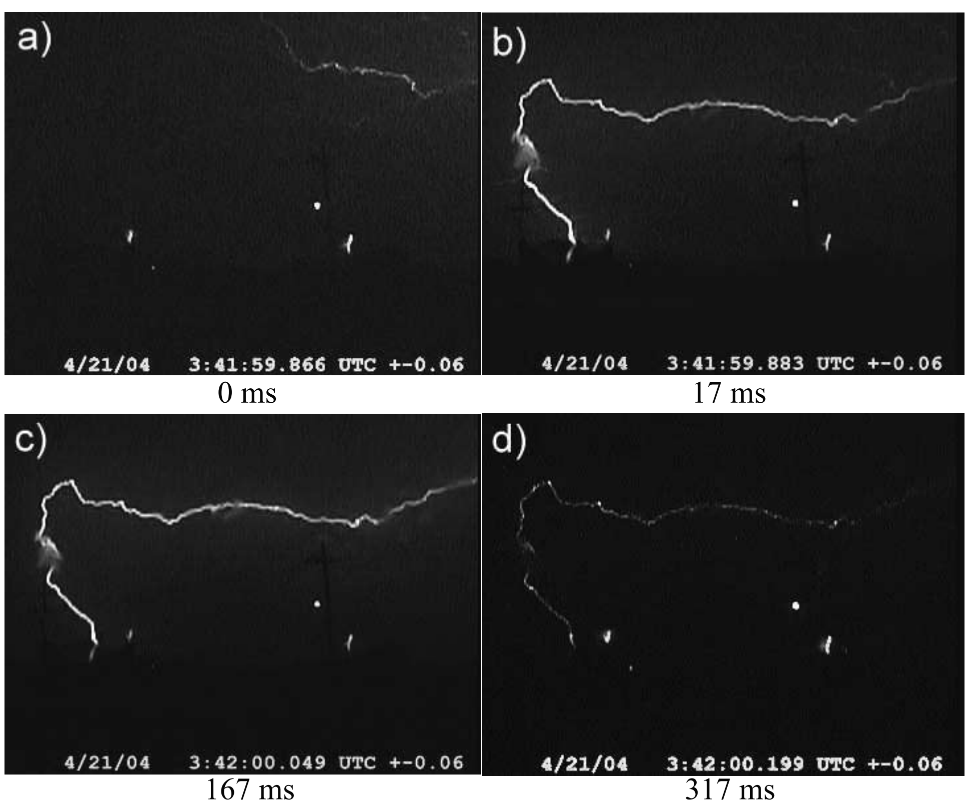


Figure 9. (a–d) Four video fields showing the luminous development of a small negative CG flash with an $I_p = -5.0$ kA. Figure 9a shows an air discharge before the CG stroke in Figure 9b. Figures 9c and 9d show how the stroke persisted for about 300 ms.

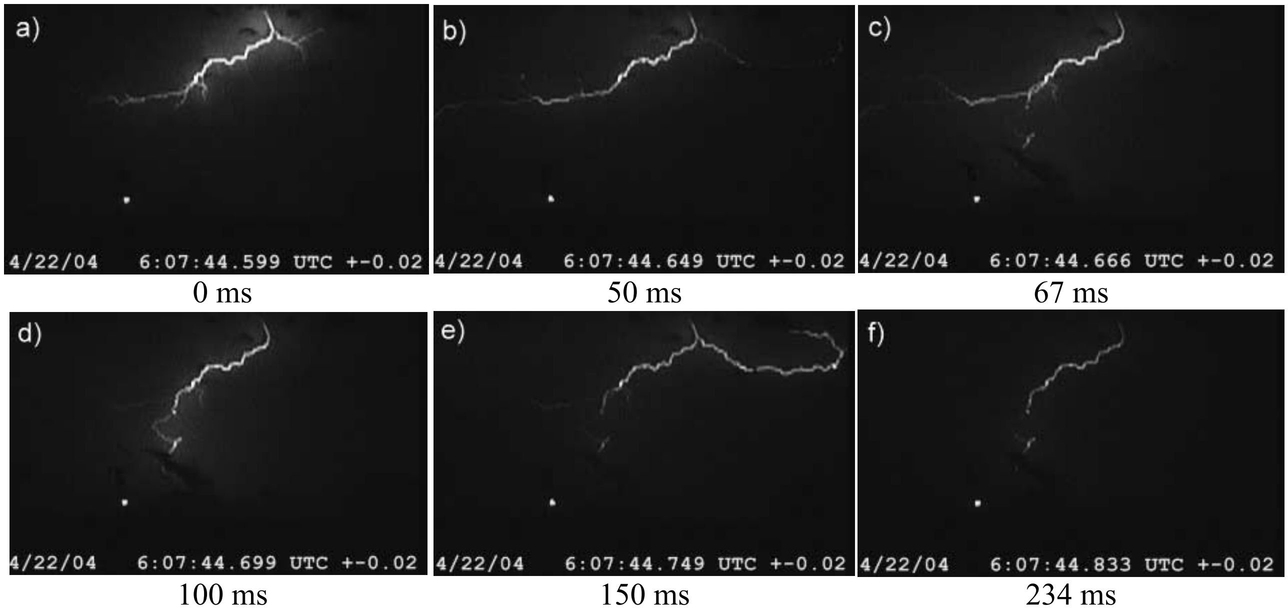


Figure 10. (a–f) Sequence of video fields showing the luminous development of the smallest negative CG flash ($I_p = -2.6$ kA). In Figure 10a an air discharge begins and continues into Figure 10b. Figure 10c shows a CG stroke that persisted for at least 318 ms. The air discharge persists through Figure 10e. Although the ground contact is obscured by (scud) clouds, the channel persisted for 316 ms, and it contained two pulsations in luminosity that resembled M components.

correction factors for the counts of unresolved subsequent strokes, the value of stroke DE, and the average multiplicity. About 13% (34/253) of the subsequent strokes were not resolved by the video camera. (We also note that this percentage is between the 4% of interstroke intervals that the NLDN reported to be less than 17 ms and the 19% that were less than 34 ms in the Tucson area in 2003.) Therefore the correction factor for estimating the true (first plus subsequent) stroke DE is 0.9 times the measured video-based value, and the correction factor for estimating the true negative flash multiplicity is 1.11 times the video-based value.

[49] The combined, 2-year average flash DE in AZ was 93% (1024/1097) and the measured stroke DE was 76% (2746/3620). If we apply the above correction factors to the entire AZ data set, the true (first plus subsequent) stroke DE in AZ is about 68%, which is the same value that *Jerauld et al.* [2005] found for rocket-triggered subsequent strokes in Florida in 2003. The 2-year average negative multiplicity measured in AZ was 3.34, and the corrected value is 3.71.

[50] The combined, 2-year average flash DE in TX-OK was 92% (339/367), and the measured stroke DE was 86% (755/882). If we apply the AZ correction factor described above to the TX-OK data set, our best estimate of the true stroke DE in TX-OK is about 77%. The 2-year average multiplicity measured in TX-OK was 2.52, and our best estimate of the correct value is 2.80. It should be noted that the correction factors derived from the O and E waveform data in AZ 2003 may not be ideal for TX-OK because these factors do depend on the distributions of the interstroke intervals and the number of ground contacts, and both of these could vary regionally.

[51] The negative multiplicities in this study are all based on counts of strokes (first and subsequent) that were observed on video, minus the sum of positive strokes and the negative strokes associated with bipolar flashes, as reported by the NLDN. These values may be biased by a small percentage of positive strokes that were not reported by the NLDN, and we can estimate the magnitude of this effect by considering the relative occurrence of small and large positive strokes in our data set. Given that only one bipolar flash was observed, and that nearly all positive flashes are single stroke, the primary effect will be from single-stroke positive flashes that were not reported. Assuming that the only reason positive strokes were not reported by the NLDN is that they had a low I_p value (<10 kA, see Figure 3), then an upper bound on the number of unreported (positive) strokes can be estimated as follows. In all 4 data sets, only 3.2% (47/1464) of the video flashes were correlated with positive NLDN reports. Of these, 4% (2/47) had an I_p < 10 kA; thus only about 0.13% (3.2% of 4%) of the positive flashes had an I_p < 10 kA. If the same fraction of video flashes was not reported by the NLDN, then an upper bound on the number of unreported positive flashes is 0.13% of 1464 flashes or 2. Clearly, our estimates of the actual number of negative strokes and the average negative multiplicity are not biased in a significant way by any unreported positive flashes.

[52] The average values of I_p (for first strokes) and the measured multiplicities of negative flashes were low in the TX-OK 2003 data set, particularly in the last recording session, and relatively few events were recorded in each session; therefore it is likely that the combination of these factors produced an underestimate of the true NLDN flash and stroke DE in TX-OK in 2003.

[53] In 2001, *Parker and Krider* [2003] measured the NLDN flash DE in southern Arizona (prior to the NLDN upgrade) and obtained a value of 71% using a coincidence window of 33.4 ms. Unbeknownst to those authors, how-

ever, the accuracy of their time synchronization was actually about 83 ms, due to an unanticipated variation in the internal clock frequency of the video camera, and because of this, their value for the flash DE should have been about 73% rather than 71% [*Kehoe and Krider*, 2004]. Now, if we compare the NLDN flash DE in 2001 with the average of all AZ measurements in 2003 and 2004 (93%), it is clear that the upgrade has significantly increased the flash DE in AZ and produced a comparable increase in the stroke DE.

[54] The flash DE in AZ after the upgrade was expected to be somewhat lower than in TX-OK, because southern Arizona is near the edge of the NLDN, and there are no sensors to the south. As noted previously, the TX-OK region has sensors in all directions, and the average distance to the nearest sensor is less than in AZ. The almost equal values of flash DE in AZ and TX-OK can be attributed to the relative paucity of low-I_p first strokes in AZ (see Figures 5 and 6), and the higher negative multiplicity (see Table 5 and Figure 6). The measured DE values in both regions are in good agreement with Vaisala estimates [*Cramer et al.*, 2004].

[55] Table 5 shows that except for the limited TX-OK 2003 data set, the NLDN stroke DE is highest for first strokes, less for the subsequent strokes that form new ground contacts, and even lower for strokes that remain in a preexisting channel to ground. These differences are expected because the distributions of I_p in these populations decrease in a similar manner (see Table 5). The mean and median values of I_p for both first strokes and subsequent strokes are consistent with the measurements of *Rakov and Uman* [1990], who found that the geometric means of the range-normalized peak radiation fields are larger for first strokes than for subsequent strokes.

[56] On the basis of the values of I_p that we have inferred from the E waveforms (see Figure 3), we conclude that the primary reason strokes are missed by the NLDN is that the peak amplitude of the stroke, or the estimated peak current, I_p, is below the detection threshold of the NLDN. Figure 3 shows that 78% of the strokes that were missed had an $|I_p|$ that was at or below 7 kA, and only 7 (12%) of the missed strokes had an $|I_p|$ that was larger than 11 kA. The minimum detectable peak current in this analysis (5 kA) is in good agreement with the model-based value of 5–6 kA in southern AZ [see *Cummins et al.*, 2006, Figure 5]. The recent NLDN upgrade has lowered the NLDN detection threshold throughout the U.S., and increased both the flash and stroke DE.

[57] Insight into the factors that effect the flash DE can be gained by considering the three flashes in the O and E study that were not detected by the NLDN. Two flashes were single stroke, and one was a three-stroke flash. Low multiplicity obviously increases the likelihood of missing all strokes in the flash, because there are fewer chances of having a stroke with a large enough $|I_p|$ to be detected. Additionally, it has been shown that negative flashes that have a low multiplicity also tend to have first strokes with a low I_p [*Rakov and Uman*, 1990; *Orville et al.*, 2002]. Both of the above factors are consistent with the characteristics of the three flashes that were missed in the O and E study.

4.2. Regional Differences in Multiplicity and Estimated Peak Current

[58] In a 10-year (1989–1998) climatology of NLDN reports before the recent upgrade, *Orville and Huffines* [2001] found that the average multiplicities in TX-OK and AZ were approximately equal. The results of our (corrected) video-based measurements show that the average multiplicities in theses regions are different, about 3.82 strokes per flash in AZ and 2.66 strokes per flash in TX-OK. The similarity of the NLDN multiplicities of *Orville and Huffines* [2001] is either due to a poor DE in AZ prior to the recent upgrade [*Parker and Krider*, 2003], or to seasonal differences in the lightning characteristics that are not reflected in our April measurements in TX-OK.

[59] *Orville and Huffines* [2001] have also reported a larger median I_p in TX-OK than in AZ (inferred from their Figure 13), and again this behavior differs from our results. Our median values of $|I_p|$ for negative first strokes in AZ and TX-OK were about 5 kA and 10 kA, respectively, less than the values reported by *Orville and Huffines* [2001]. This decrease is probably due to the lowering of the minimum detectable I_p by the upgrade, and the effect is larger in TX-OK because that region has a greater fraction of small first strokes ($|I_p| \leq 10$ kA) than AZ (see Figure 5). A detailed evaluation of seasonal variations in the lightning characteristics in both AZ and TX-OK will be needed before final conclusions can be made about the causes of the regional differences that we observed.

4.3. Storm-to-Storm Variability in Lightning Parameters

[60] Tables 1–4 show that there were considerable variations in the average negative multiplicity (as measured on video) and the average I_p (as measured by the NLDN) among the different recording sessions. We have performed linear regressions over the different recording sessions to determine if there was a correlation between the flash DE and the flash multiplicity, the average I_p, and the product of the flash multiplicity and I_p for each campaign in our data set. The 2004 AZ campaign showed a good correlation between the flash DE and average I_p ($r^2 = 0.78$), and a weaker correlation ($r^2 = 0.63$) between the flash DE and the product of multiplicity and I_p. There was no apparent correlation between the flash DE and multiplicity ($r^2 = 0.21$). None of the other 3 campaigns showed any correlation between the flash DE and average I_p, multiplicity or the product of the latter two parameters.

[61] The primary factor affecting the differences in DE between recording sessions appears to be sample size, and this is illustrated in Figure 11. The solid and dashed curves in Figure 11 show the lower statistical bounds on the expected variation in the measured flash DE values, as a function of the number of flashes, using the conventional statistical definition of a one-sided confidence interval for an estimated parameter, $\hat{X}$, given n independent observations in the presence of noise:

$$\hat{X} \pm K_\alpha \frac{\sigma_x}{\sqrt{n}}.$$

Here K_α is the value of the normalized random variable (unit variance and zero mean) for the desired confidence limit (α), and σ_x is the true standard deviation [*Bowker and Leiberman*, 1972]. In this analysis, we view the product $K_\alpha \cdot \sigma_x$ as an unknown constant, k, and we define $\hat{X}$ as the "best" estimate of the flash DE (95%), based on the average

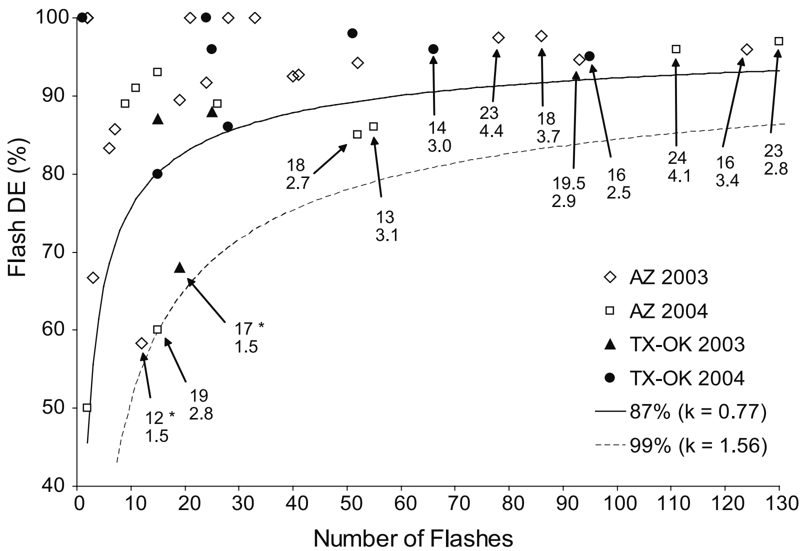


Figure 11. Plot of the NLDN flash DE versus the number of flashes recorded in each session. The numerical labels give the average I_p of negative first strokes (top value) and the average video multiplicity of negative flashes (bottom value). The solid curve shows the lower bound for 87% of the sessions, and the dashed curve shows the lower bound for 99% of the sessions (as described in section 4.3). The two sessions marked with an asterisk are near the edge of the 99% confidence level and appear to represent actual storm-to-storm variations. Note the large variability in the values of I_p and multiplicity for sessions that had less than 60 flashes and that all points below the solid curve have a mean $|I_p|$ that is less than 20 kA.

DE for the six sessions that had more than 80 flashes; this results in the expression $0.95 - k/\sqrt{n}$, where n is the number of flashes recorded in a session. The bounding curves in Figure 11 show the expected reduction in the variation of the estimates of DE as n increases, assuming that the observations are uncorrelated. The solid curve is a lowest possible bound for 87% (34/39) of the observations, and it is associated with a $k = 0.77$. If we assume Gaussian errors, then the 99th percentile would have $k \approx 1.56$ (assuming the 87th percentile corresponds to a $k = 0.77$). Three of the sessions that fall between the 87th and 99th percentile confidence bounds are from AZ in August 2004, when the fourth closest NLDN sensor was not operational. We showed in section 3.1.2 that the flash DE was slightly lower during this period of the AZ 2004 campaign (89.6% versus 95.5%), and the values in Figure 11 are consistent with that interpretation. Apart from the August 2004 sessions in AZ, there are two other sessions that fall near the 99th percentile confidence bound (those marked with an asterisk) which suggests that these sample populations may also be "different." Both sessions have an average I_p that is less than the median values in the other campaigns, and they also have unusually low multiplicities (both 1.5). In fact, the farthest outlier of these two has the lowest "paired" average I_p and multiplicity (12 kA and 1.5) of all the recording sessions with 10 or more flashes, and was obtained in the AZ 2003 campaign.

[62] Figure 11 clearly shows that there is a relationship between the flash DE and the total number of flashes recorded in a session, and the variation in the DE between sessions decreases as the number of flashes increases. The average flash DE in the 8 recording sessions that had 66 or more flashes is 96%. Note that these 8 sessions include both AZ and TX-OK and had a wide range of multiplicities and estimated peak currents. The average negative I_p in these 8 sessions ranged from 14 kA to 24 kA (5 of the 8 were below 20 kA), and the video multiplicities ranged from 2.5 to 4.4 strokes per flash, yet the flash DE only varied between 95% and 98%. On the basis of Figure 11, we conclude that the NLDN can be used to estimate the (space and time) average (and median) I_p and the multiplicity of negative flashes as long as the storms produce of the order of 60 flashes or more. Figure 11 also shows that there can be significant storm-to-storm variations in the average I_p and multiplicity in the same region.

[63] *Idone et al.* [1998] observed significant storm-to-storm variations in the NLDN DE near Albany, NY, and concluded that this was due to "a natural variability inherent in lightning return stroke characteristics." In a study of 6 separate storms in Brazil, *Saba et al.* [2006] also found large storm-to-storm variations in multiplicities, ranging from 2.2 to 6 strokes per flash. Further analyses of the variations in lightning parameters from storm-to-storm and with season will be the subject of a future study.

4.4. Low-Amplitude, Single-Stroke NLDN Reports

[64] In our evaluation of the classification of low-amplitude NLDN reports, we have noted that some of the events that showed no luminous activity on video (NL in Tables 6–8) may actually be CG flashes that were not detected because of intervening rainfall, obscuration by terrain, or the fact that some NLDN reports might have been outside the camera field of view because of errors in the camera pointing direction or large NLDN location errors for low I_p events. We typically used a small camera aperture when recording in the daytime to prevent saturation of the camera, and if a lightning channel was very faint, it might not have exceeded the detection threshold of the video system. Since the brightness of a lightning channel is roughly proportional to the peak current

[*Idone and Orville*, 1985], there is undoubtedly a detection bias in the daytime, and that bias is probably why a much larger fraction of low-amplitude strokes was detected at night relative to the daytime (see Tables 7 and 8). In the future, we plan to add a second video camera to the experiment that will operate with a wide aperture, possibly in conjunction with optical filters, to reduce the day/night bias.

[65] In section 3.6, we have seen that at most about 7% of the small positive reports with $I_p \leq 10$ kA were produced by CG strokes, and not more than 30% with an I_p between 10 kA and 20 kA were CGs. When $I_p > 20$ kA, at least 66% and at most 94% of the positive reports were due to CG strokes, depending on whether the events that exhibited no luminous activity (NL) are included in the statistics or not. Clearly, there is no unique threshold for classifying a small-positive report as a CG stroke, but an I_p of 15 kA appears to be the value where the number of false CG reports equals the number of correct reports.

[66] In our discussion of small-negative events in section 3.7 (see Tables 7 and 8), we have seen that if NL events are included in the counts, then at least 50% of the small-negative NLDN reports are CGs, and if the NLs are not included, then 87% are CGs. We have also noted that 66% (27/41) of the combined daytime reports showed no luminosity, in contrast to 27% (17/63) in the combined nighttime reports. This detection bias produces a significant overestimate of the misclassified NLDN reports, unless the "NL" events are excluded. Also, 18 NLs in the AZ 2004 daytime data set came from one storm that was close to the maximum range for detecting low-amplitude strokes on video (the storm was 30–40 km away). Clearly, in the future, it would be highly desirable to study the NLDN classifications further and to combine video measurements such as ours with other lightning data, particularly those from VHF lightning mapping systems [*Krehbiel et al.*, 2000; *Thomas et al.*, 2004; *Demetriades et al.*, 2002], and time-correlated lightning waveforms [*Ishii et al.*, 2006]. A preliminary study by *Johnson and Mansell* [2006] has demonstrated the feasibility of using VHF lightning mapping for classification studies, and this work also suggests that some supercell storms may produce a large number of small negative reports that are misclassified by the NLDN.

4.5. NLDN Multiplicity

[67] In the Introduction, we noted that in some regions of the U.S. the NLDN upgrade has produced no change or even a decrease in the average negative multiplicity, and this observation can now be addressed. In this paper, we have seen that the NLDN upgrade has improved both the flash and stroke DE of CG lightning and that the improvements in DE are due to better detection of low-amplitude strokes (see section 4.1). We have also seen (Figure 6) that flashes with small negative first strokes (I_p between -10 kA $< I_p < 0$ kA) tend to have (on average) a much lower multiplicity than flashes with a larger I_p, and they are more likely to be single-stroke flashes. It is also clear from our study of small negative, single-stroke NLDN reports that some of these reports are produced by cloud pulses. At this point, we can conclude that both of these factors counteract the increase in NLDN multiplicity that comes from the improved detection of low-amplitude subsequent strokes.

[68] It should be noted that the NLDN upgrade has not changed the negative NLDN multiplicity in TX-OK, but it did increase the multiplicity in southern Arizona. In general, the average multiplicity in a given region will depend on the distributions of the peak fields that are radiated by first and subsequent strokes, the local NLDN detection threshold in that region, and the degree to which isolated pulses in cloud flashes are misclassified as negative CG strokes by the NLDN.

[69] We will conclude by noting that since the characteristics of CG lightning have significant variations from storm to storm as well as between geographic regions and/or seasons, a single (global) distribution may not be sufficient for describing the characteristics of any given lightning parameter, like the multiplicity or I_p. Clearly, in the future, it would be interesting to conduct additional studies in AZ, TX-OK, and other regions in order to quantify the NLDN performance and the characteristics of CG lightning under a variety of weather regimes.

[70] **Acknowledgments.** One of the authors (C.J.B.) has submitted this research in partial fulfillment of the requirements for a M.S. degree in atmospheric sciences at the University of Arizona. This work has been supported in part by the Vaisala Thunderstorm Unit, Tucson, AZ, and the NASA Kennedy Space Center, grant NAG10-302. The authors would like to thank Charles D. Weidman for his assistance with the instrumentation and John Cramer for providing the NLDN flash and stroke data.

References

Bowker, A. H., and G. J. Leiberman (1972), *Engineering Statistics*, Prentice-Hall, Upper Saddle River, N. J.

Cramer, J. A., K. L. Cummins, A. Morris, R. Smith, and T. R. Turner (2004), Recent upgrades to the U. S. National Lightning Detection Network, paper presented at the 18th International Lightning Detection Conference, Vaisala, Helsinki, Finland, 7–9 June.

Cummins, K. L., and E. A. Bardo (2004), On the relationship between lightning detection network performance and measured lightning parameters, paper presented at the 1st International Conference on Lightning Physics and Effects, Braz. Natl. Inst. of Space Res., Belo Horizonte, Brazil, 7–11 Nov.

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

Cummins, K. L., J. A. Cramer, C. J. Biagi, E. P. Krider, J. Jerauld, M. A. Uman, and V. A. Rakov (2006), The U. S. National Lightning Detection Network: Post-upgrade status, paper presented at the Second Conference on Meteorological Applications of Lightning Data, Am. Meteorol. Soc., Atlanta, Ga., 29 Jan. to 2 Feb.

Demetriades, N. W. S., M. J. Murphy, and K. L. Cummins (2002), Early results from the Global Atmospherics, Inc. Dallas-Fort Worth Lightning Detection and Ranging (LDAR-II) research network, paper presented at the Sixth Symposium on Integrated Observing Systems, Am. Meteorol. Soc., Orlando, Fla., 13–17 Jan.

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

Idone, V. P., D. A. Davis, P. K. Moore, Y. Wang, R. W. Henderson, M. Ries, and P. F. Jamason (1998), Performance evaluation of the U.S. National Lightning Detection Network in eastern New York: 1. Detection efficiency, *J. Geophys. Res.*, *103*, 9045–9055.

Ishii, M., M. Saito, F. Fujii, A. Sugita, and N. Itamoto (2006), Investigation on LEMP observed by JLDN, paper presented at the 19th International Lightning Detection Conference, Vaisala, Tucson, Ariz., 26–27 April.

Jerauld, J., V. A. Rakov, M. A. Uman, K. J. Rambo, D. M. Jordan, K. L. Cummins, and J. A. Cramer (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.

Johnson, E. V., and E. R. Mansell (2006), Three-dimensional lightning mapping of the central Oklahoma supercell on 26 May 2004, paper presented at the Second Conference on Meteorological Applications of Lightning Data, Am. Meteorol. Soc., Atlanta Ga., 29 Jan. to 2 Feb.

Kehoe, K. E., and E. P. Krider (2004), NLDN performance in Arizona, paper presented at the 18th International Lightning Detection Conference, Vaisala, Helsinki, Finland, 7–9 June.

Krehbiel, P. R., R. J. Thomas, W. Rison, T. Hamlin, J. Harlin, and M. Davis (2000), GPS-based mapping system reveals lightning inside storms, *Eos Trans. AGU*, *81*(3), 21–22, 25.

Orville, R. E., and G. R. Huffines (2001), Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98, *Mon. Weather Rev.*, *129*, 1179–1193.

Orville, R. E., G. R. Huffines, W. R. Burrows, R. L. Holle, and K. L. Cummins (2002), The North-American Lightning Detection Network (NALDN)—First results: 1998–2000, *Mon. Weather Rev.*, *130*, 2098–2109.

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

Rachidi, F., J. L. Bermudez, M. Rubinstein, and V. A. Rakov (2004), On the estimation of lightning peak currents from measured fields using lightning location systems, *J. Electrostatics*, *60*, 121–129.

Rakov, V. A. (2004), Lightning return-stroke speed: A review of experimental data, paper presented at the 27th International Conference on Lightning Protection, Inst. R. Météorol. de Belgique, Avignon, France, 13–16 Sept.

Rakov, V. A., and M. A. Uman (1990), Some properties of negative cloud-to-ground lightning flashes versus stroke order, *J. Geophys. Res.*, *95*, 5447–5453.

Rakov, V. A., and M. A. Uman (2003), *Lightning: Physics and Effects*, Cambridge Univ. Press, New York.

Saba, M. M. F., M. G. Ballarotti, and O. Pinto Jr. (2006), Negative cloud-to-ground lightning properties from high-speed video observations, *J. Geophys. Res.*, *111*, D03101, doi:10.1029/2005JD006415.

Schulz, W., K. Cummins, G. Diendorfer, and M. Dorninger (2005), Cloud-to-ground lightning in Austria: A 10-year study using data from a lightning location system, *J. Geophys. Res.*, *110*, D09101, doi:10.1029/2004JD005332.

Thomas, R. J., P. R. Krehbiel, W. Rison, S. J. Hunyady, W. P. Winn, T. Hamlin, and J. Harlin (2004), Accuracy of the lightning mapping array, *J. Geophys. Res.*, *109*, D14207, doi:10.1029/2004JD004549.

Thottappillil, R., J. D. Goldberg, V. A. Rakov, M. A. Uman, R. J. Fisher, and G. H. Schnetzer (1995), Properties of M components from currents measured at triggered lightning channel base, *J. Geophys. Res.*, *100*, 25,711–25,720.

Uman, M. A., D. K. McLain, and E. P. Krider (1975), The electromagnetic radiation from a finite antenna, *Am. J. Phys*, *43*, 33–38.

Wacker, R. S., and R. E. Orville (1999), Changes in measured lightning flash count and return stroke peak current after the 1994 U.S. National Lightning Detection Network upgrade: 1. Observations, *J. Geophys. Res.*, *104*, 2151–2158.

C. J. Biagi, K. L. Cummins, and E. P. Krider, Institute of Atmospheric Physics, University of Arizona, PO Box 210081, Room 542, 1118 East 4th Street, Tucson, AZ 85721-0081, USA. (krider@atmo.arizona.edu)

K. E. Kehoe, Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, OK 73019-1011, USA.