2010 21st International Lightning Detection Conference 19 - 20 April • Orlando, Florida, USA 3rd International Lightning Meteorology Conference 21 - 22 April • Orlando, Florida, USA

INFLUENCE OF THE CN TOWER ON THE LIGHTNING ENVIRONMENT IN ITS VICINITY

A.M. Hussein[1,2], S. Jan[1], V. Todorovski[1], M. Milewski[1], K.L. Cummins[3] and W. Janischewskyj[2]

[1]Electrical and Computer Engineering, Ryerson University, Toronto, Canada; ahussein@ee.ryerson.ca
[2]Electrical and Computer Engineering, University of Toronto, Toronto, Canada
[3]Atmospheric Sciences, University of Arizona, AZ, USA

Abstract - The CN Tower has been the center of tourism in Toronto since it first opened to the public on June 26, 1976. Standing at 553 meters, it is Canada's most recognizable icon. Could there be a down side to this incredible structure? Does it attract more lightning; potentially putting the surrounding area in its vicinity in harm's way, or does it provide lightning protection to this area? Although, extensive investigations have been performed concerning the characteristics of lightning strikes to the CN Tower, not much attention has been given to the characteristics of lightning strikes in the vicinity of the tower or the influence the tower has on the lightning environment around it. This paper is planned to help in addressing these questions. Using lightning data reported in 2005 by the combined Canadian Lightning Detection Network (CLDN) and U.S. National Lightning Detection Network (NLDN), an extensive analysis of lightning activity within 100 km of the tower has been carried out. A comparison between the characteristics of CN Tower strikes and those of strikes occurring in its vicinity is also included. Excluding CN Tower strokes, a lower stroke density in the area of up to a few kilometres from the tower was observed, when compared with other nearby areas. Although the tower may provide some protection to the area in its immediate vicinity, a larger data set is needed to confirm this initial interesting finding. Furthermore, the waveform parameters of the lightning electromagnetic pulse (LEMP) generated by return strokes to the tower are compared with those generated by non-CN Tower strokes. In addition to the marked increase in the frequency of occurrence of CN Tower LEMP, its wavefront peak and maximum rate-of-rise are found to be substantially larger than those characterizing non-CN Tower LEMP. Therefore, electronic and communication systems located in the vicinity of a very tall structure may be exposed to much higher levels of electromagnetic interference resulting from its LEMP.

1 INTRODUCTION

Although the lightning ground flash density (GFD), number of cloud-to-ground flashes per square kilometre per year, in the Toronto area is about two, the Canadian National (CN) Tower, usually receives many tens of lightning strikes yearly [1]. For example, video records show that in 1991, the CN Tower was hit with 80 flashes, 24 of which occurred within 100-minute period [2].Therefore, the CN Tower presents one of the best sites in the world to observe lighting for the purpose of studying tall-structure lightning, including the derivation of extensive statistics concerning the visual characteristics of lightning flashes [2], [3], and the waveform parameters of the lightning current [4] and its generated electromagnetic pulse [5]. Furthermore, return-stroke current models for lightning to elevated objects [6], [7] and the performance characteristics of the combined CLDN and NLDN (referred to as the North American Lightning Detection Network, or NALDN) have been evaluated based on CN Tower lightning return-stroke data [8].

Lightning strikes to the CN Tower have been observed for over 30 years. In 1991, five recording stations were in operation to simultaneously capture the CN Tower lighting parameters; namely, the current derivative at the tower using a Rogowski coil and RTD 710A Tektronix digitizers, the vertical component of the electric field and the two horizontal components of the magnetic field, 2 km north of the tower, using broadband active sensors and RTD 710A Tektronix digitizers, the return-stroke velocity, RSV, using a photodiode system, and two 2-dimensional images of the flash trajectory using VHS (video home system) cameras from directions that are approximately perpendicular to each other [1]. Figure 1 shows the CN Tower and the locations of these instruments.

Since 1996, an expansion of the measurement facilities has been taking place. A 1000-frame/sec high-speed camera (HSC) was acquired in 1996 (Fig. 1). In 1997, a noise-protected current sensing system consisting of a new Rogowski coil and an optical fibre link was installed at the tower (Fig. 1). In 2001, two LeCroy LT362 double-channel digitizers with 2-ns time resolution and large segmented memories were acquired to record the lighting return-stroke current derivative at the tower and its corresponding electromagnetic field. For time synchronization of CN Tower lightning recording instruments, four Global Positioning System (GPS) units were also acquired. In 2008, a new two-channel current recording system was installed at the tower with much larger memory per channel (50-M points) for the possibility of measuring the continuing current.

August 19, 2005 was a Toronto famous stormy day, which provided much of the data reported in this investigation [9]. Using the NALDN data, the ground flash density for that day (24-hour period, Toronto local time) within 100 km radius around the CN Tower was 0.4 flashes per square km, whereas the ground flash density in the same area for the whole year (2005) was 2.38; that is to say 16.8% of lightning flashes during 2005 occurred on August 19. Also, the stroke density within the same area on August 19 was 0.98, which amounts to 17% of the stroke density during the whole year (5.79). Furthermore, during the same day, the CN Tower was struck by six flashes containing 37 return strokes, 22 of which were reported by the NALDN. It is also interesting to note that the average flash multiplicity for CN Tower flashes on August 19 was 6.17 according to CN Tower lightning data, whereas it was 3.67 according to NALDN data. In contrast, the average flash multiplicity for non-CN Tower flashes within 100 km from the tower was 2.46 during the same day and 2.43 for the whole year. Therefore, a CN Tower flash, on average, contains more strokes than a non-CN Tower flash.

In order to assess the protection effects of the tower on the area within its immediate vicinity, a careful study of NALDN flash data within the area of up to 20 km from the tower indicated that the distances between estimated locations of strokes within the same flash can be large, reaching close to 10 km in several cases. Therefore, the influence of the existence of the tower on the lightning environment in its vicinity has been found to be more properly investigated using the NALDN stroke data rather than its flash data.

Given the large attractive radius of the tower, it is possible to assume that stroke density near the tower is disturbed, and that the characteristics of flashes/strokes in the immediate vicinity of the tower may differ from those of more-distant strikes. This paper emphasizes the comparison between the characteristics of lightning strikes (e.g., flash multiplicity, stroke density, polarity, and peak current) to the CN Tower and those of strikes occurring in the tower's vicinity. Also, the wavefront parameters (peak and maximum rate-of-rise) of lightning electromagnetic pulses (LEMPs) generated by CN Tower return strokes are compared with those of LEMPs generated by return strokes to much shorter objects or to ground in the vicinity of the tower [10].

2 Current Derivative and Field Measurement Systems

The return-stroke current derivative resulting from a strike to the CN Tower is measured using two Rogowski coils. The older, 3-m long, 40-MHz coil was installed at the 474-m AGL in 1990, and encircles one-fifth of the tower's steel pentagonal structure [4]. Because of the symmetry, the captured signal is assumed to correspond to 20% of the total current derivative. The coil is connected to one channel of an 8-bit, 2-ns, double-channel LeCroy LT362 digitizer, located at a recording station (403-m AGL, Fig. 1), via a tri-axial cable. In 1997, a newer, 6-m long, 20-MHz coil was installed at the 509-m AGL. The new coil encircles the whole steel structure of the tower and is connected to the LeCroy digitizer via an optical fiber link [4]. During the 2005 lightning season, the new Rogowski coil was not operational; therefore, the current data used here were obtained via the old Rogowski coil.

Since 1991, the vertical component of the electric field (E_z) and the azimuthal component of the magnetic field (H_φ), resulting from lightning strikes to the CN Tower and strikes occurring in its vicinity, have been captured by broadband active field sensors [11]. The sensors are placed on the roof of a 20-m high building, located 2 km north of the tower, and are connected to a double-channel LeCroy LT362 digitizer via coaxial cables. The electric field sensor is an active, hollow, hemispherical-shaped monopole with a sensitivity of 1.44 V/(kV/m). The electric field sensor has low and high 3-dB cut-off frequencies of 47 Hz and 100 MHz, respectively. The magnetic field sensor is of the small-loop antenna type with a sensitivity of 0.166 V/(A/m). It has low and high 3-dB cutoff frequencies of 697 Hz and 150 MHz, respectively. The circular loop of the magnetic field sensor is oriented in such a way as to capture the azimuthal component of the magnetic field generated by CN Tower lightning strokes.

In 2004, GPS units were added for time synchronization of CN Tower lightning recording instruments, including the current derivative and field measurement systems, allowing a time stamping, accurate to 1 μs, for each recorded return stroke. In the past, before the acquisition of the GPS units, it was a tedious task to match lightning flashes recorded by different instruments, let alone trying to match individual return strokes. Therefore, it was quite difficult to experimentally correlate the characteristics of CN Tower lightning parameters to each other and to the North American Lightning Detection Network (NALDN) data [8], [11].

3 Lightning Parameters at and in the Vicinity of the CN Tower

This section concentrates not only on analyzing the NALDN lightning data (combined NLDN and CLDN) within up to 100 km radius from the tower for the entire year of 2005, but also on these data recorded on the famous Toronto stormy day of August 19th, 2005. These data were reported by a nearly-equal number of lightning sensors in the U.S. and Canada. The lightning parameters addressed here are stroke location, stroke monthly and hourly rate of occurrence, stroke density and polarity, flash multiplicity, and stroke current peak.

A. Stroke Location

Given the large attractive radius of the tower, it is possible to assume that the density of strokes near the tower is disturbed, and that the characteristics of flashes/strokes in the immediate vicinity of the tower may differ from those of more-distant strikes. A careful investigation of NALDN flash and stroke data in the area around the tower indicated that locations of strokes within a single flash can be many kilometres apart. Therefore, the influence of the existence of the tower on the lightning environment in its vicinity has been found to be more properly examined using NALDN stroke data rather than its flash data [9].

Figures 2 shows the locations of all non-CN Tower return strokes reported by the NALDN on August 19, 2005 within 20 km radius from the CN Tower, plotted in a North versus East Cartesian format. The NALDN strike location data has been converted from latitude and longitude in degrees to north-south and east-west in km. The CN Tower is then placed at the origin. (The area within 20 km radius from the tower is divided into 4 km octants.) It is important to emphasize that the 22 NALDN-detected strokes that struck the tower during August 19, 2005 are not included in the figure. It is also worth mentioning that the CN Tower is located almost on the north shore of Lake Ontario as shown in Fig. 3, quite close to the U.S.-Canada border. Figure 2 clearly shows the substantially low stroke density on the lake side. Figure 4 includes the locations of all non-CN Tower strokes reported by the NALDN on the same day within 100 km from the tower.

B. Monthly and Hourly Return-Stroke Rate

Figure 5 presents the percentage of the number of CN Tower and non-CN Tower strokes, within 100 km radius around the CN Tower, for each of the 2005 months. The total number of strokes that were detected by the NALDN during that year was 181787. The figure shows that most of the lightning (93% of return strokes) took place during the summer months, June-August, peaking in August.

Figure 6 displays the local-time 24-hourly lightning activity within a 100 km radius around the CN Tower. The percentage of the number of strokes (CN Tower and non-CN Tower) is plotted as a function of time during the day. The figure shows that most lightning activity occurred in the afternoon, peaking around 4 p.m.

C. Ground Stroke Density

The variation of stroke density with distance and angle from the CN Tower was studied, in order to assess the protection effects of the tower on the area within its immediate vicinity. The stroke density (number of strokes/km^2) within 20 km from the CN Tower during August 19, 2005 (excluding tower strokes) is presented in Fig. 7. The angles were divided into north (representing the area from – 45^o to 45^o from the north), east (representing the area from – 45^o to 45^o from the east), etc. The lines in Fig. 7 represent the stroke density as a function of distance towards north, west, east and south. The solid dark line, representing the variation of the stroke density for all angles, shows a reduction in stroke density within a few kilometers from the tower, a trend seen in most directions except towards south. The presented data suggests that the tower may provide some protection to the area in its immediate vicinity, although these observations are confounded by the natural increasing gradient of lightning density from the lake. Obviously, more data are needed to confirm this interesting observation.

In Fig. 8, the solid line represents the variation of negative-stroke density for all angles, whereas the variation of positive-stroke density is represented by a dashed line. The figure indicates a substantially lager density of negative strokes around the tower in comparison with positive strokes. It is worth mentioning that positive strokes are rarely measured at the CN Tower [12].

For the same day, August 19, 2005, Fig. 9 presents the stroke density (negative and positive combined), as a function of distance within 100 km radius from the tower. On the larger scale, the figure describes the spatial distribution of lightning strokes. It also shows clear reduction in stroke density in the immediate vicinity of the tower.

D. Flash Multiplicity

The flash multiplicity is defined as the number of strokes per flash. The variation of flash multiplicity as a function of distance from the tower during August 19, 2005 is shown in Fig. 10. Although 6 flashes containing 37 return strokes struck the tower that day, with an average multiplicity of 6.17, only the strokes detected by the NALDN (22 out of 37) were considered in the calculation of the multiplicity of CN Tower flashes, which is presented by an 'X' on the vertical axis in Fig. 10. The figure shows that flash multiplicity of CN Tower strikes (3.67, based on NALDN-detected strokes) is clearly higher than that for strikes around the tower. Figure 10 also shows some reduction in flash multiplicity in the immediate vicinity of the tower. This finding is interesting and needs further investigations.

E. Peak Current

Figure 11 shows the average NALDN estimated peak current for negative and positive strokes versus distance from the tower (0-20 km) for August 19, 2005. For CN Tower strokes, the NALDN estimated peak currents were used to calculate the average peak current (23.9 kA, indicated with "X" in Fig. 11) rather than those obtained from the tower's current measurement system. It is worth mentioning that the NALDN was found to overestimate the current peak measured at the tower [8], [13].

4 CN Tower LEMP Versus Non-CN Tower LEMP

A. LEMP Waveforms

Figure 12 presents an example of the vertical electric field of a lightning electromagnetic pulse (LEMP) generated by a CN Tower lightning return stroke, measured 2 km north of the tower on August 19, 2005 [11]. Also, Fig. 13 shows an example of the electric field generated by a non-CN Tower return stroke that, according to the NALDN, was located 10.62 km away from the field measurement station. (It is worth mentioning that because of the presence of high-frequency noise related to nearby broadcasting stations, fifth-order elliptic software low pass filters with a cut-off frequency of 5 MHz were used to de-noise the measured field waveforms before presenting them in Figs. 12 and 13 [11].)

B. Statistical Analysis of LEMP Waveforms

The cumulative statistical distributions presented here are based on the electric field signals measured 2 km north of the CN Tower on August 19, 2005. These measured field signals consist of 6 flashes to the tower, containing 36 return strokes, and 8 non-CN Tower flashes containing 11 return strokes. However, based on the NALDN flash data, the 8 non-CN Tower flashes contain 27 strokes (i.e., 16 non-CN Tower strokes did not trigger the CN Tower field measurement system). The distance of the 27 non-CN Tower strokes from the electric field measurement system ranged from 3.2 to 20.2 km.

Figure 14 presents the cumulative statistical distributions of the number of strokes per flash for field signals generated by CN Tower flashes (solid line) and for those generated by non-CN Tower flashes based on the CN Tower field measurement system (dash-dot line), as well as for those generated by non-CN Tower flashes based on NALDN flash data (dashed line). The figure indicates the inability of the field measurement system of capturing all strokes in a flash because the elevated trigger level. The comparison between the solid and dashed lines in Figure 14 points to a marked increase in flash multiplicity for CN Tower lightning as compared with that for non-CN Tower lightning. This marked increase in flash multiplicity, when combined with the obvious great increase in the number of flashes striking a tall structure [2] in comparison with flashes to objects in its vicinity, leads to a much higher frequency-of-occurrence of LEMPs in the vicinity of a tall structure.

In order to properly compare the electric field wavefront peaks and maximum rates of rise associated with CN Tower return strokes with those associated with non-CN Tower return strokes, the electric field peaks and maximum rates-of-rise of non-CN Tower strokes are normalized so that they would correspond to field peaks and maximum rates of rise measured 2 km away from the locations of strokes [5], using an inverse-distance relationship. Furthermore, since lightning current peaks vary considerably from one stroke to another, the electric field wavefront peak and maximum rate-of-rise are normalized with the corresponding peak current measured at the tower for CN Tower strokes or estimated by the NALDN for non-CN Tower strokes.

Figure 15 presents the cumulative statistical distribution of the normalized wavefront electric field peaks generated by CN Tower strokes as compared with those generated by non-CN Tower strokes. The figure shows a substantial increase in the normalized electric field peak for CN Tower strokes as compared with that for non-CN Tower strokes. This finding reflects the enhancement of field peaks for tall towers noted in [8] and [13].

In attempting to derive the cumulative statistical distribution of the normalized maximum rate-of-rise of the electric field generated by non-CN Tower strokes, it was noticed that the field maximum rate-of-rise for negative strokes (6 out of the 11 measured field strokes) substantially exceeds that for positive strokes (5 field strokes). This finding necessitated the derivation of separate statistics for each category. Figure 16 presents the cumulative statistical distribution of the normalized maximum rate-of-rise of the electric field generated by CN Tower strokes (solid line) as compared with that generated by non-CN Tower strokes. In case of the measured electric field signals of non-CN Tower strokes, separate statistics for negative strokes (6 strokes, dashed line) and positive strokes (5 strokes, dashed-dot line) are displayed in the figure. Figure 16 shows a remarkable increase in the normalized electric field maximum rate-of-rise associated with CN Tower strokes as compared with that associated with non-CN Tower strokes. Furthermore, the normalized maximum rate-of-rise of the electric field generated by non-CN Tower negative strokes notably exceeds that for positive strokes.

A summary of the cumulative statistical distributions shown in Figs. 14-16 is presented in Tables 1 and 2. Table 1 compares the characteristics of CN Tower and non-CN Tower flashes and strokes, recorded by the field measurement system on August 19, 2005. For each parameter, the table shows the values of the minimum, the maximum, the average (mean), the median (obtained from data points) and the median that corresponds to the 50% probability level (calculated from the cumulative statistical distribution). The table indicates that the average flash multiplicity for CN Tower flashes is more than four times that for non-CN Tower flashes. Also, the 50% probability level for the normalized electric field peak resulting from CN Tower strokes is more than three times that resulting from non-CN Tower strokes. Furthermore, the average normalized electric field maximum rate-of-rise resulting from CN Tower strokes is about seven times that resulting from non-CN Tower strokes.

Table 2 presents detailed comparison between the characteristics of non-CN Tower negative flashes/strokes and those of non-CN Tower positive flashes/strokes, which were recorded by the field measurement system on August 19, 2005. It is noticed in Table 2 that the number of strokes in a positive flash is markedly lower than that for negative flashes. Table 2 also shows that the normalized maximum rate-of-rise for positive field strokes is substantially lower than that for negative field strokes. The median peak-field and rate-of-rise results for the non-CN Tower strokes are in general agreement with values reported by Krider et al. 1996 [14]. The median peak-field value for the six negative strokes of 0.0405 (kV/m)/kA becomes 12 V/m when converted to a 100 km distance and multiplied by the ~15 kA median value of the non-CN Tower strokes. The median value found by Krider et al. over salt water in Florida was 8.2 V/m. Similarly, the median rate-of-rise for the 6 negative non-CN Tower strokes in this study converts to ~20 V/m/µs; Krider et al. found a mean value of ~39 V/m/µs for a quite symmetrical distribution in the range ~15-75 V/m/µs. The somewhat smaller median rate-of-rise found it this study is likely due to the somewhat longer propagation paths over lower-conductivity ground, coupled with the large uncertainty in the small dataset. We note that the median rate-of-rise for the 39 negative CN Tower strokes in this study converts to ~60 V/m/µs, which is at the ~95th percentile of values found by Krider et al. [14].

In addition to the much higher frequency-of-occurrence of LEMP resulting from CN Tower lightning, remarkable increases in its field peak and maximum rate-of-rise in comparison with those for the LEMP generated by non-CN Tower lightning have been clearly shown in Figs. 14-16 and Table 1. This large difference cannot be explained by the attenuation of high-frequency fields produced by the additional 3.2-20.2 km propagation distance for the non-CN Tower strokes. Therefore, electronic and communication systems located in the vicinity of a very tall structure may be exposed to substantially higher levels of electromagnetic interference (EMI) resulting from its lightning-generated electromagnetic pulse.

Table 1: Flash multiplicity and LEMP electric field wavefront parameters of CN Tower and non-CN Tower lightning

	CN Tower (6 flashes containing 36 strokes)			Non-CN Tower (8 flashes containing 11 strokes)		
	Number of Strokes/flash	E/I [(kV/m]/kA	(dE/dt)/I [(kV/m)/μs]/kA	Number of Strokes/flash	E/I [(kV/m]/kA	(dE/dt)/I [(kV/m)/μs]/kA
Minimum	1	0.0704	0.0598	1	0.0121	0.0099
Maximum	10	0.0913	0.3453	3	0.0447	0.0798
Mean	6	0.0827	0.1911	1.37	0.0278	0.0297
Median (data)	6	0.0832	0.1855	1	0.0248	0.0131
Median (graph)	7.5	0.0831	0.1905	1.67	0.0250	0.0136

Table 2: Flash multiplicity and LEMP electric field wavefront parameters of non-CN Tower positive and negative lightning

	Non-CN Tower (positive, 5 strokes)			Non-CN Tower (negative, 6 strokes)		
	Number of Strokes/flash	E/I [(kV/m]/kA	(dE/dt)/I [(kV/m)/μs]/kA	Number of Strokes/flash	E/I [(kV/m]/kA	(dE/dt)/I [(kV/m)/μs]/kA
Minimum	1	0.0121	0.0099	1	0.0203	0.0106
Maximum	1	0.0251	0.0131	3	0.0447	0.0798
Mean	1	0.0213	0.0110	2	0.0332	0.0452
Median (data)	1	0.0230	0.0106	2	0.0345	0.0466
Median (graph)	–	0.0239	0.0109	–	0.0405	0.0675

5 Conclusions

Although, numerous analyses have been performed concerning the characteristics of lightning strikes to the CN Tower, not much attention has been given to the comparison between the characteristics of lightning strikes to the tower and those for strikes occurring in its vicinity. This paper has addressed many relevant questions, including the influence of the tower on the lightning environment in its vicinity. Using the 2005 lightning data from the combined CLDN and NLDN for the area of up to 100 km from the tower, an extensive investigation of lightning activities in the vicinity of the tower has been presented. A comprehensive statistical analysis of flash/stroke characteristics (e.g., flash multiplicity, and stroke location, density, monthly rate, hourly rate, polarity and peak current) of strikes occurring in the vicinity of the CN Tower has been carried out. Excluding CN Tower strokes, there appears to be a reduction in the stroke density in the area up to a few km from the tower in comparison with other areas. Although the tower seems to provide some protection to the area in its immediate vicinity, more data is needed to confirm this interesting finding. Also, some decrease in flash multiplicity within the immediate vicinity of the tower was found, which also needs further investigations.

In addition to a much higher frequency of occurrence of the lightning electromagnetic pulse (LEMP) resulting from CN Tower lightning, remarkable increases have been found in its normalized electric field wavefront peak and maximum rate-of-rise in comparison with those for LEMPs generated by non-CN Tower lightning. Therefore, electronic and communication systems located in the vicinity of a very tall structure may be exposed to much higher levels of EMI resulting from its lightning-generated electromagnetic pulse.

The presented statistics may assist in the evaluation of the risk posed by LEMP to sensitive electronic devices and circuits in the vicinity of a tall structure.

ACKNOWLEDGMENTS

The authors wish to thank Environment Canada for their generous permission to use Canadian Lightning Detection Network (CLDN) data. This work was partially supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada, which is gratefully acknowledged. Furthermore, the authors would like to thank Davide Pavanello, Emanuel Petrache, Ivan Boev, Talha Pervez, Saad Faisal and Faizan Jabbar for their great help in acquiring and processing the 2005 CN Tower lightning data.

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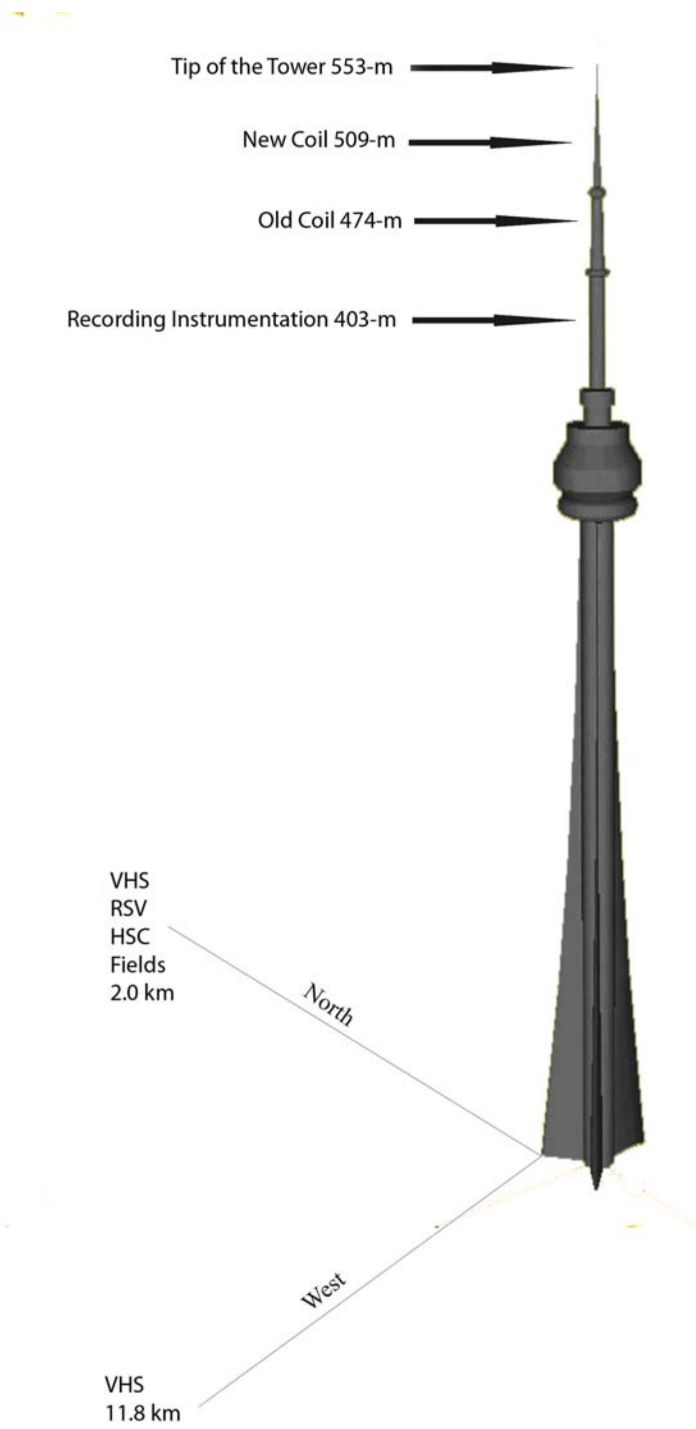

Figure 1: The CN Tower and locations of instruments.

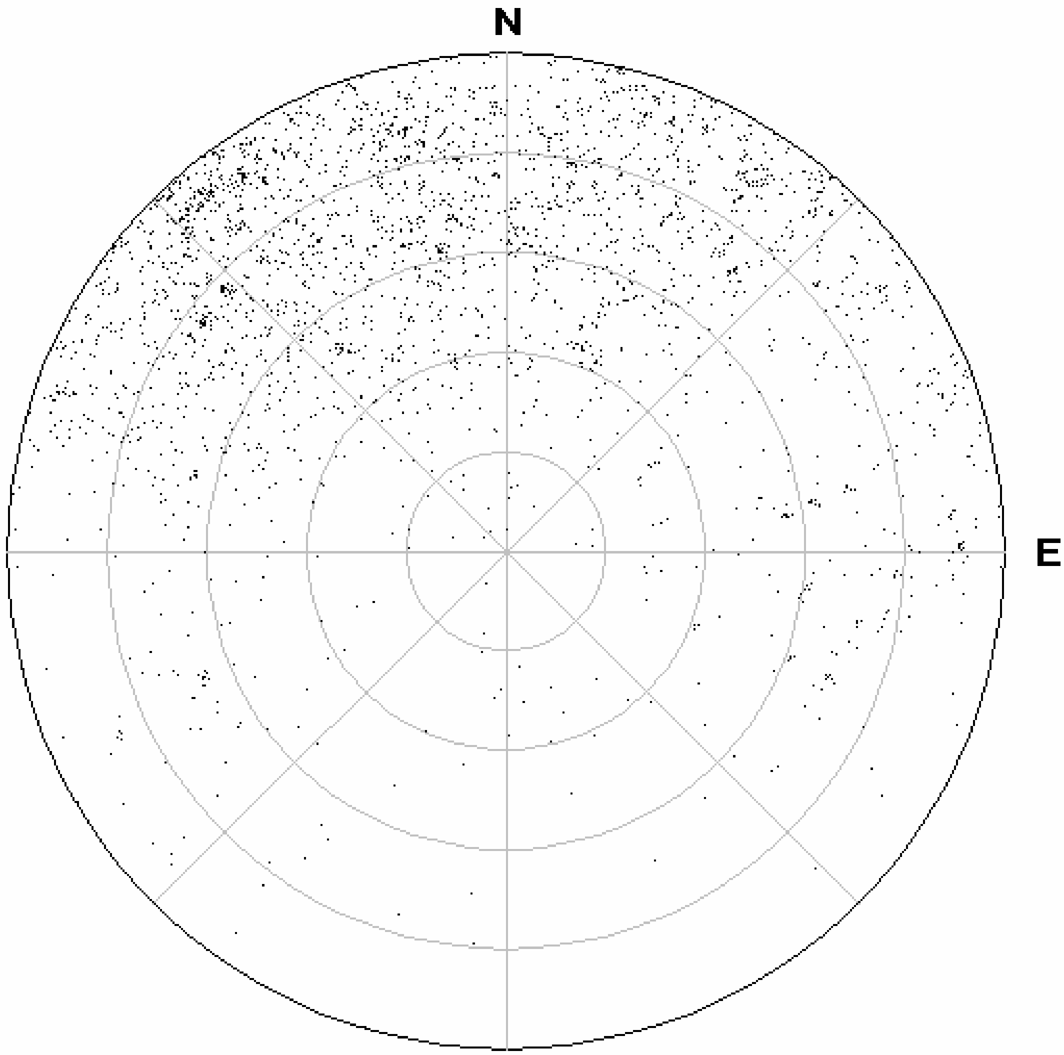

Figure 2: Location of strokes within 20 km radius around CN Tower – using 4 km grid – reported by the NALDN on August 19, 2005 excluding 22 CN strokes (the total number of the Non-CN Tower strokes is 2702).

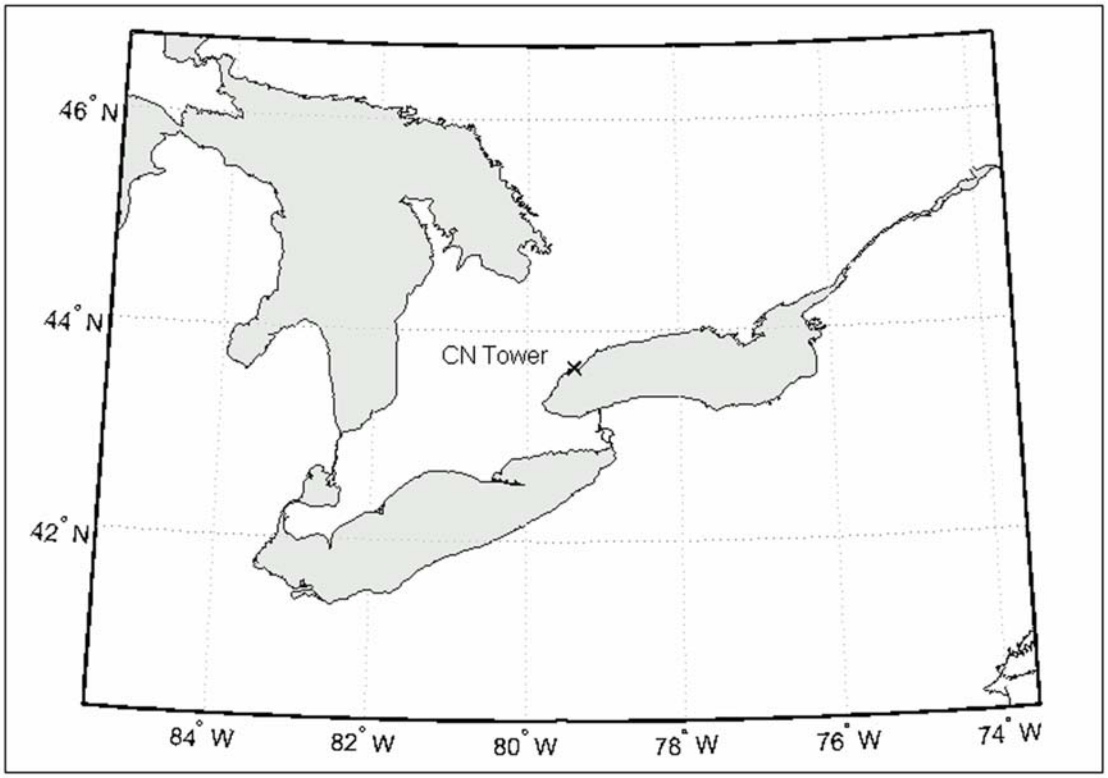

Figure 3: Map showing the location of the CN Tower in the vicinity of Lake Ontario, Canada.

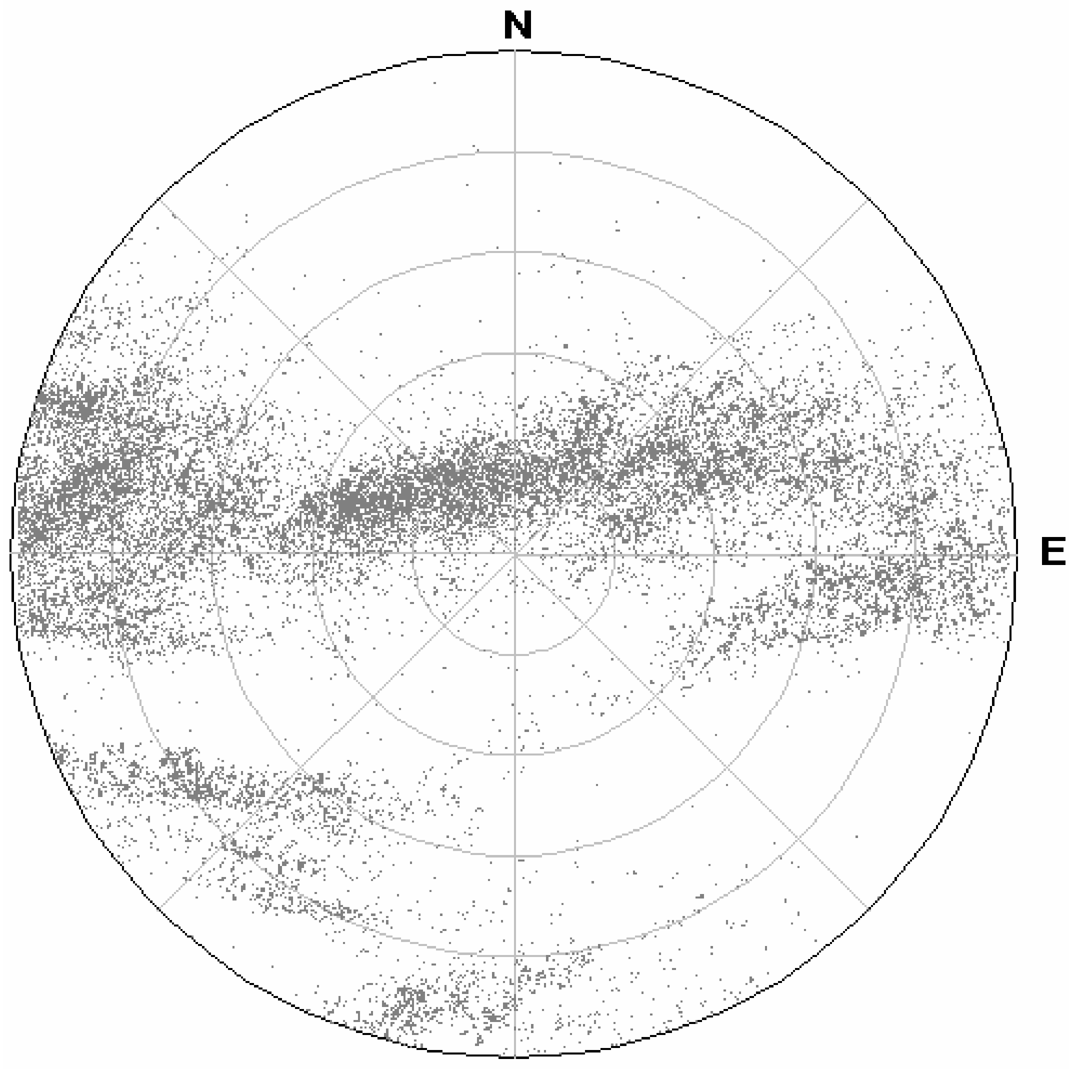

Figure 4: Location of strokes within 100 km radius around CN Tower – using 20 km grid – reported by the NALDN on August 19, 2005 excluding 22 CN strokes (the total number of the Non-CN Tower strokes is 30867).

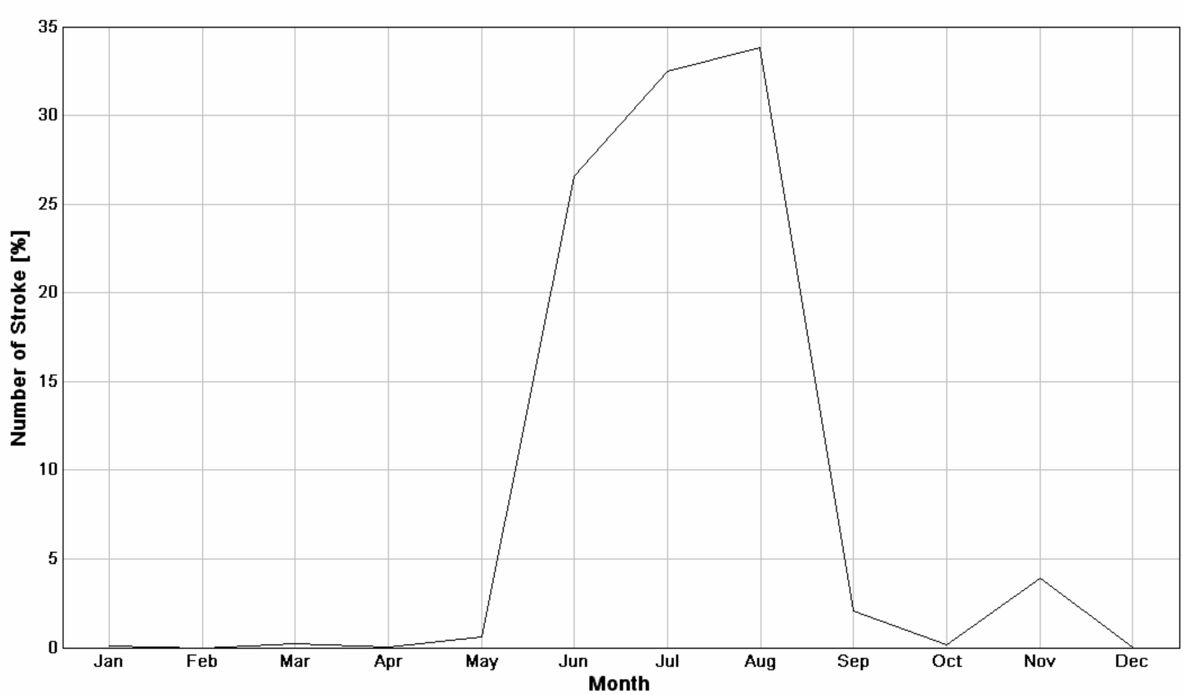

Figure 5: Monthly distribution of the percentage of strokes, within 100 km from the CN Tower during 2005 (total number of strokes is 181787).

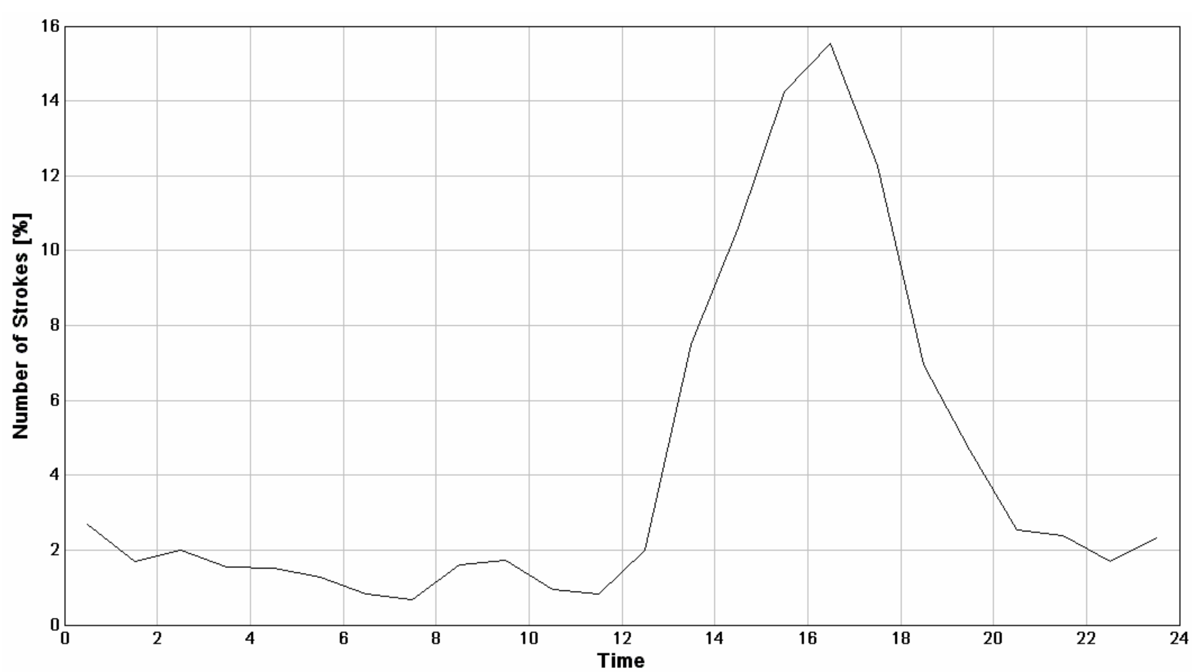

Figure 6: Hourly distribution of the percentage of strokes, within 100 km from the CN Tower during 2005.

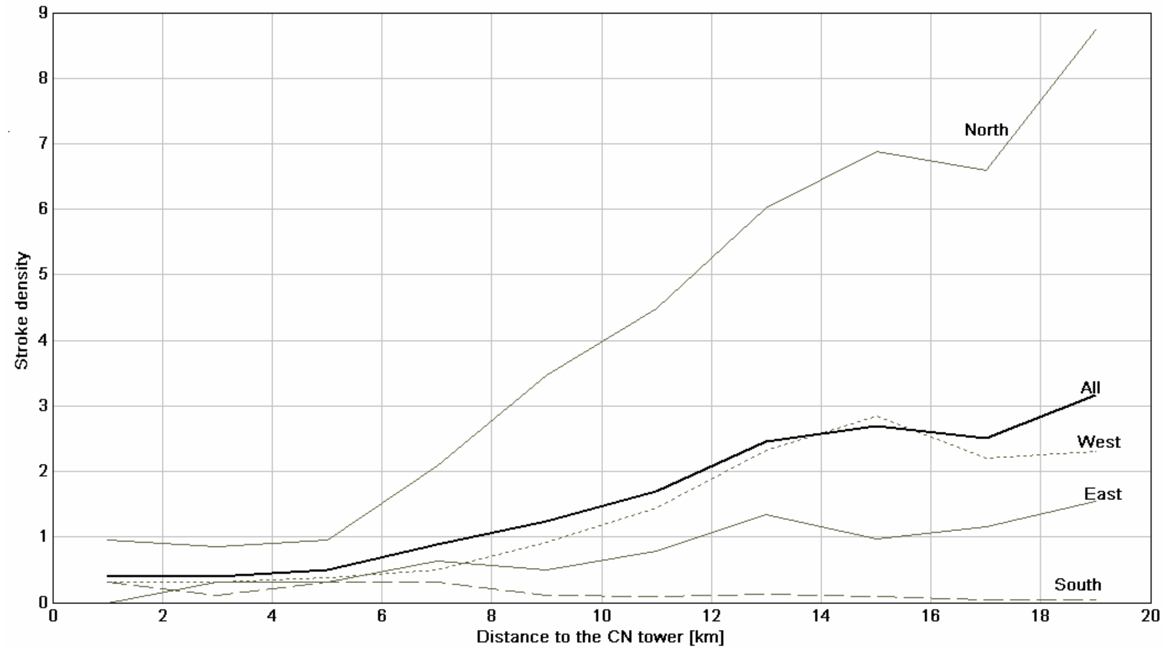

Figure 7: Density of strokes (occurring on August 19, 2005) as a function of distance from the CN Tower, excluding tower strokes (data size: 2702 strokes).

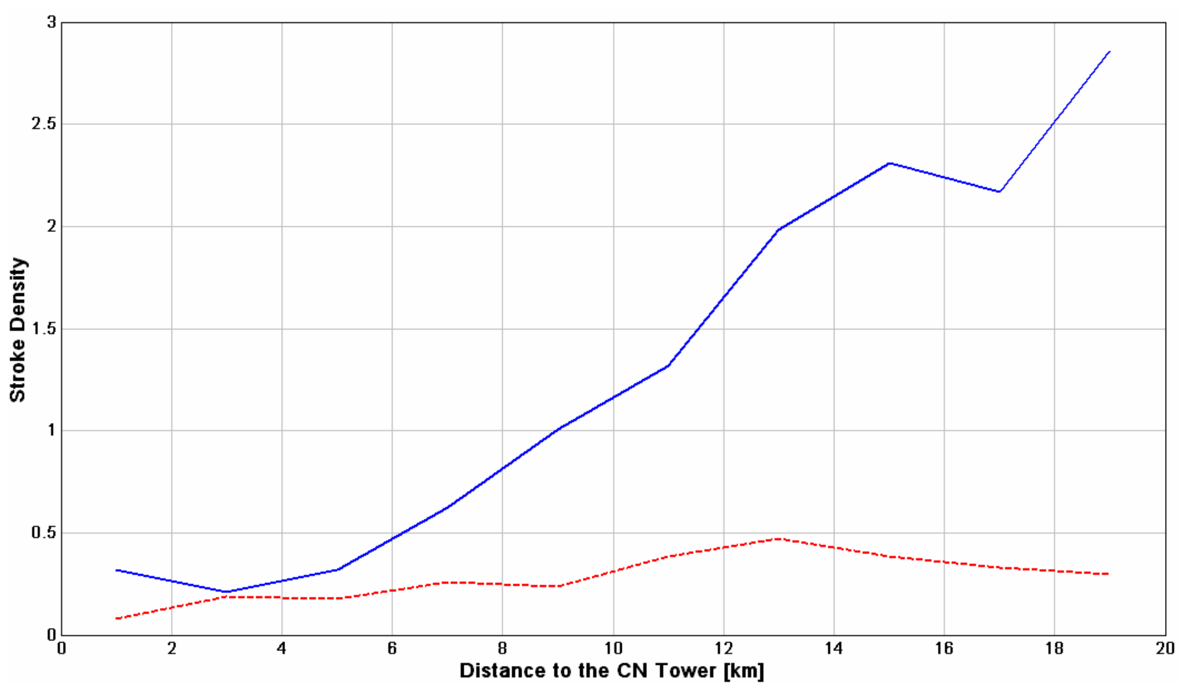

Figure 8: Densities of negative and positive strokes (occurring on August 19, 2005) as functions of distance from the CN Tower, excluding tower strokes (414 positive strokes, dashed line, 2288 negative strokes, solid line).

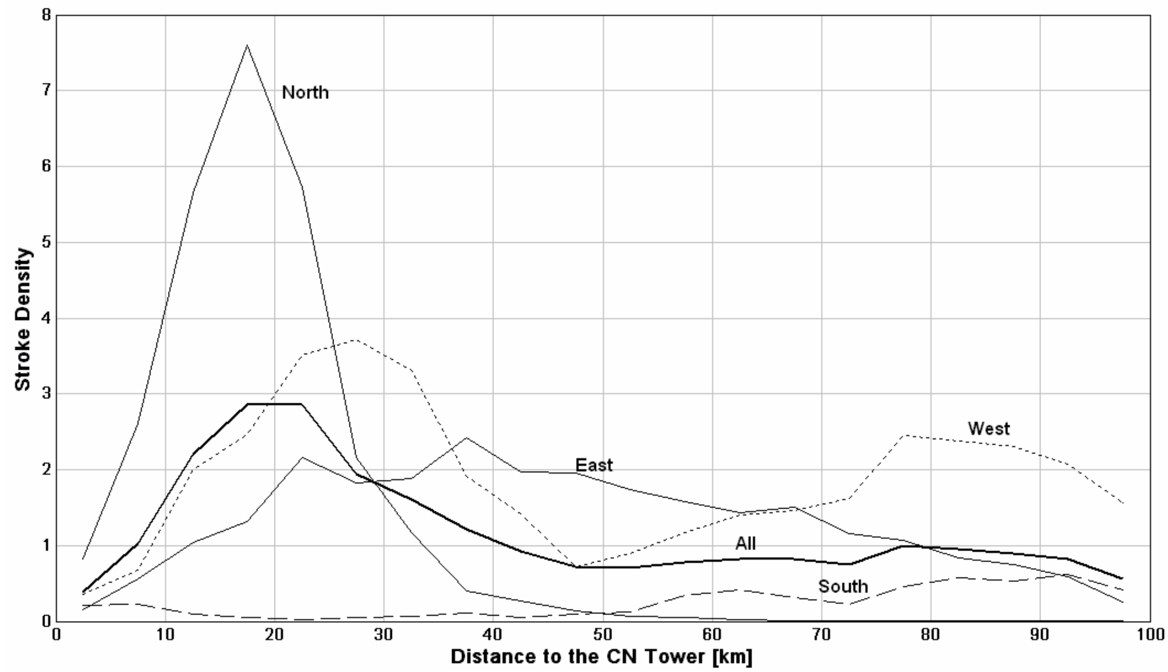

Figure 9: Density of strokes (negative and positive combined), occurring on August 19, 2005, as a function of distance from the CN Tower, up to 100 km (30,821 strokes).

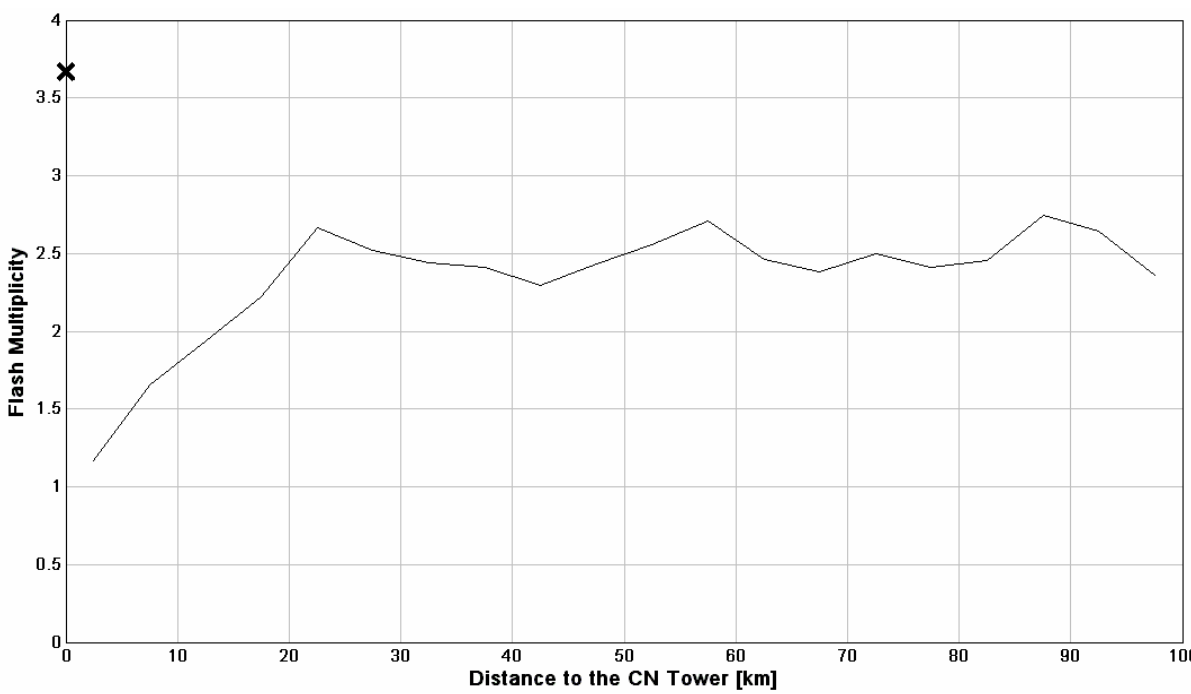

Figure 10: Flash multiplicity as a function of distance within 100 km from the tower for Aug 19, 2005 (excluding CN Tower flashes). The CN Tower flash multiplicity during the same day according to NALDN data is presented with an 'X' on the vertical axis.

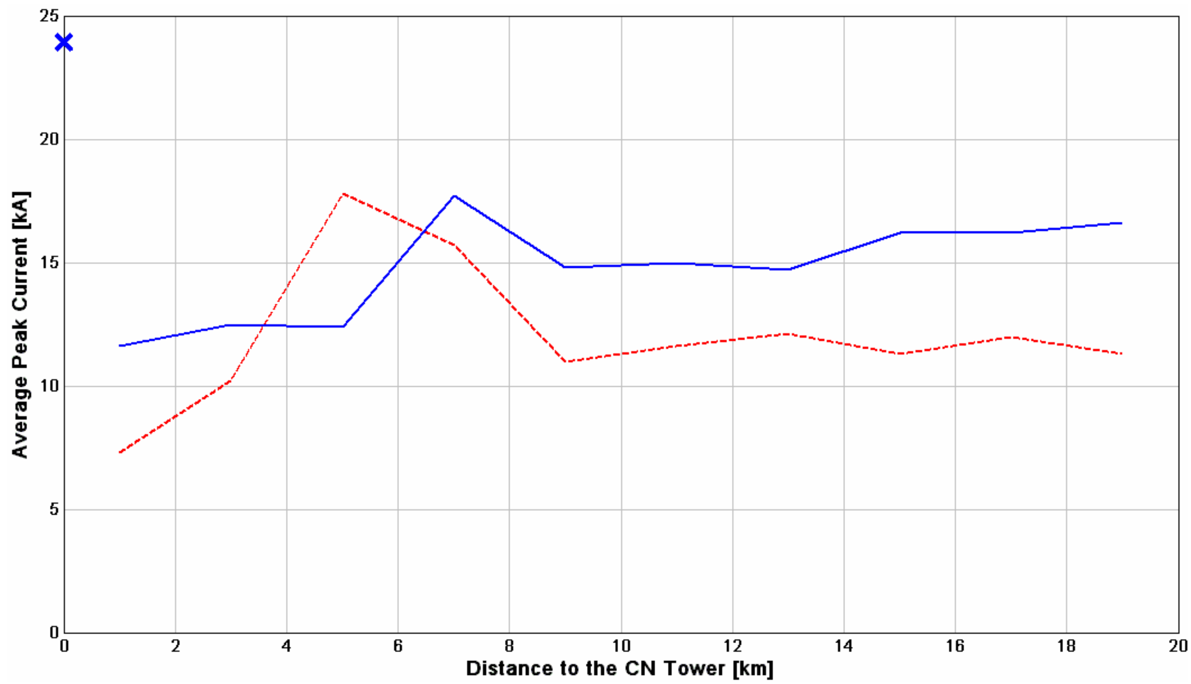

Figure 11: Average peak current variation with distance to the CN tower for negative and positive strokes (August 19, 2005), excluding CN Tower strokes. The average peak current for CN Tower NALDN detected strokes (all negative) is presented with an ‘X’ on the vertical axis.

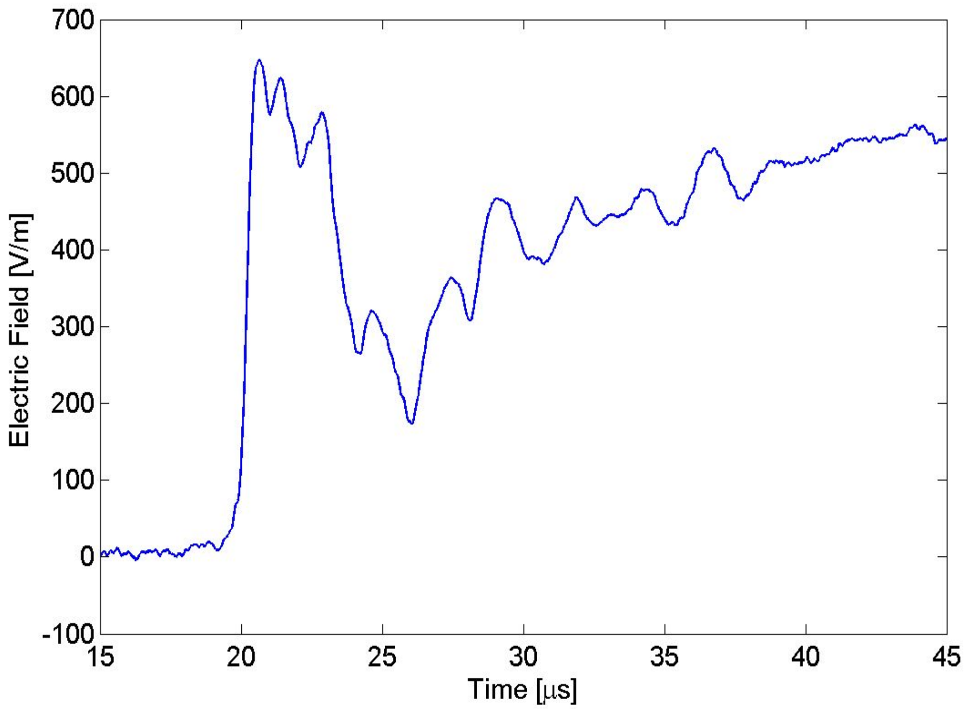

Figure 12: The electric field generated by a CN Tower lightning stroke, August 19, 2005 at 14:11:41.

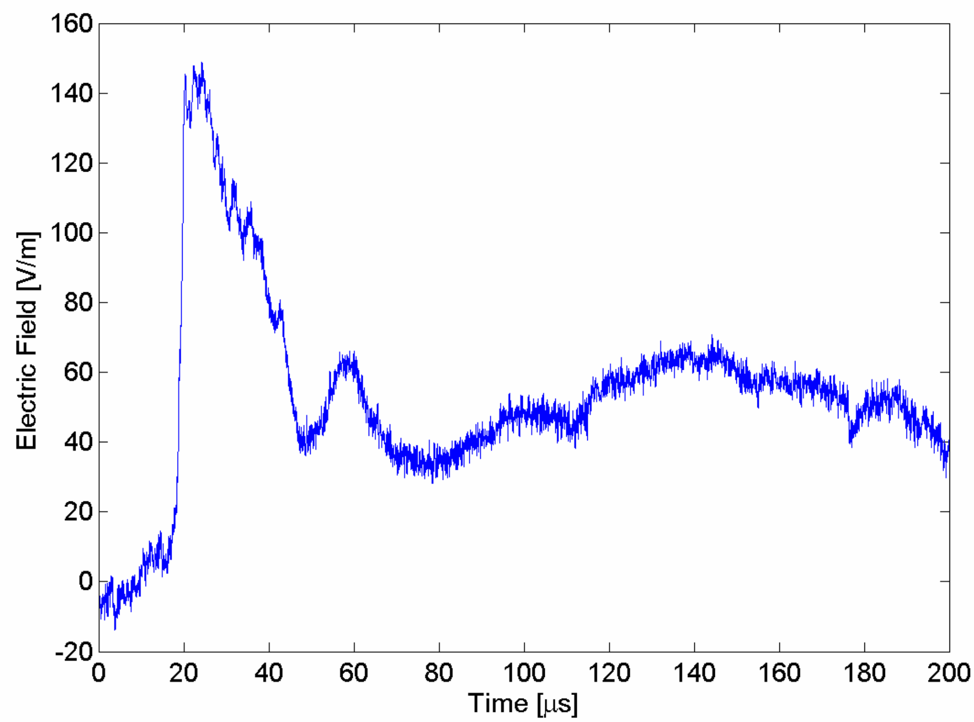

Figure 13: Typical electric field waveform generated by a non-CN Tower lightning stroke.

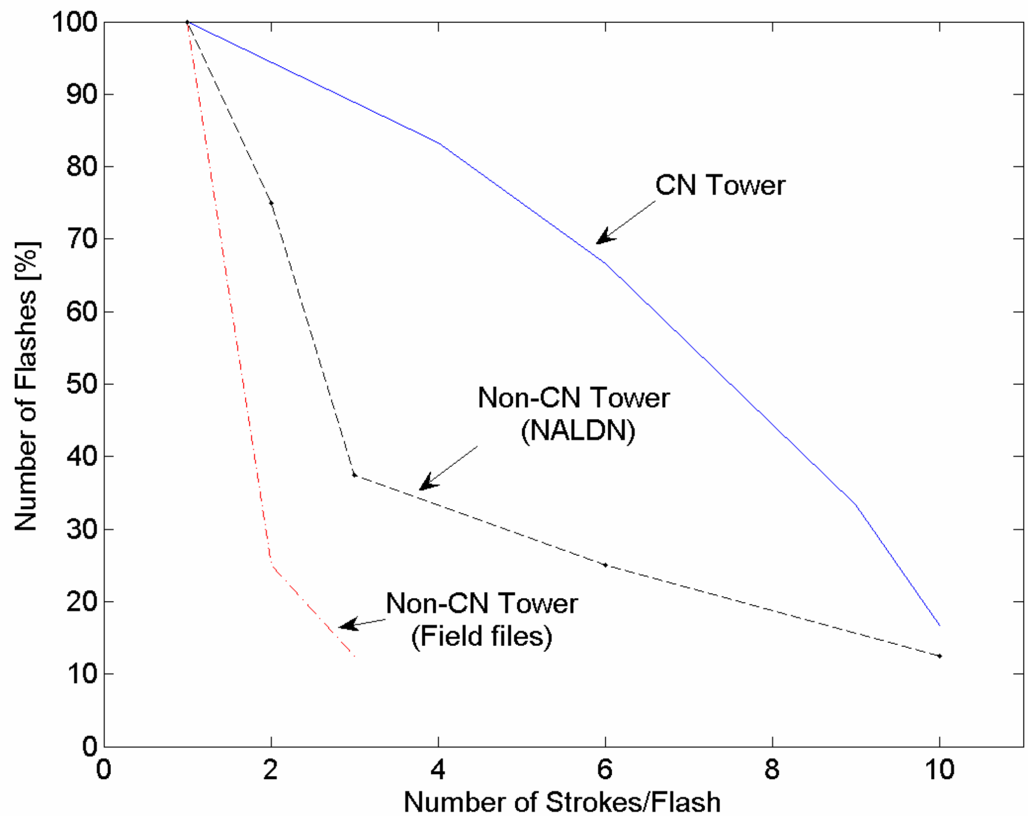

Figure 14: Number of return strokes per flash for 6 CN Tower flashes, containing 36 strokes (solid line), and 8 non-CN Tower flashes, containing 11 strokes (based on measured field data, dash-dot line) and 21 strokes (based on NALDN flash files, dashed line).

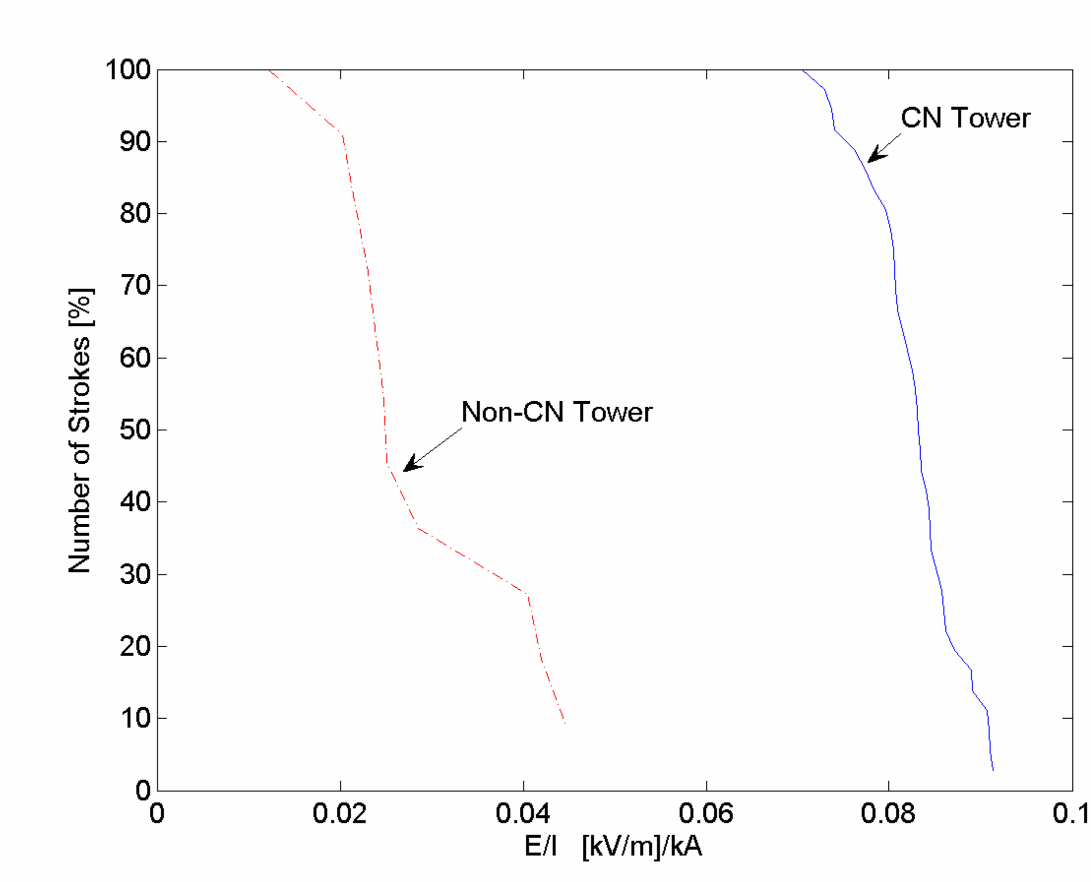

Figure 15: Normalized electric field peak for CN Tower strokes (36 strokes) and non-CN Tower strokes (11 strokes).

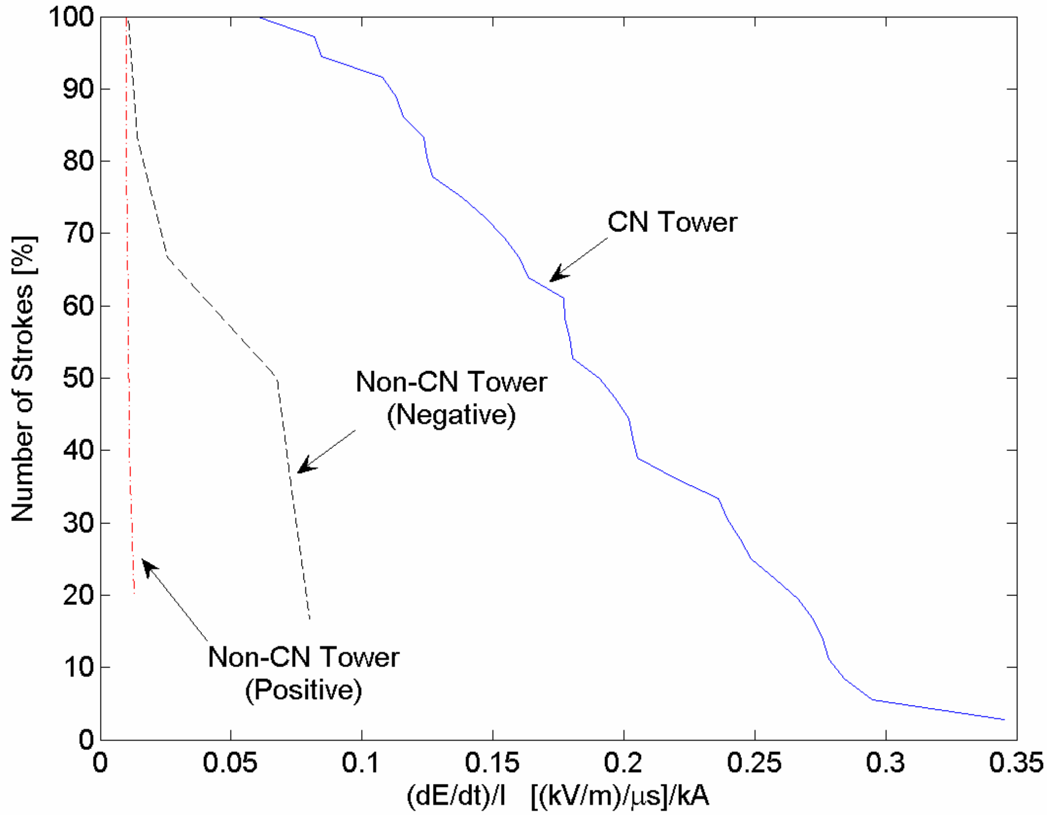

Figure 16: Normalized electric field maximum rate-of-rise for CN Tower strokes (36 strokes) and non-CN Tower positive strokes (5 strokes) and negative (6 strokes) strokes.