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Waveform Characteristics of Electromagnetic Fields Generated by Lightning to the CN Tower

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Abstract - Broadband, high resolution measuring systems have simultaneously captured the lightning current derivative at the CN Tower and the lightning-generated electromagnetic pulse (LEMP) in its vicinity since 1991. Cumulative statistics of LEMP waveform parameters (field peak, risetime to field peak and pulse width at the 50% level of the field peak) of return-strokes to the Tower during the last four years are derived. The presented statistical results will assist in the establishment of more sophisticated protective measures against interference due to LEMPs, especially those generated from lightning occurring at elevated objects.

Keywords: Lightning to tall structures, lightning-generated electromagnetic pulse, electromagnetic interference.

I. Introduction

The Toronto Canadian National (CN) Tower, at a height of 553 m, is the tallest freestanding structure in the world. Although the local lightning flash density (number of flashes per square kilometre per year) in Toronto is less than 2, the Tower receives many tens of strikes each year [1,2]. During the 1991 lightning season, for example, VHS video records showed that the CN Tower was hit with at least 72 flashes, 24 of which occurred within 100 minutes in the early morning of July 7. Therefore, the CN Tower presents one of the best sites in the world to observe lightning for the purpose of studying the physics of the lightning phenomenon and to collect characteristics of visual parameters [2,3], of currents [4,5] and of lightning-generated electromagnetic fields [6,7]. Furthermore, the verification and development of lightning return-stroke models can be established using data from lightning to tall structures, like the CN Tower, where the current can be measured [8,9].

Lightning strikes to the CN Tower have been observed since 1978, two years after its erection. In 1989, a new phase of the CN Tower lightning observation commenced. By the beginning of the summer of 1991, five measuring stations were in operation to simultaneously capture the most important lightning parameters, namely, the return-stroke current derivative at the Tower (using a Rogowski coil), the vertical component of the electric field (E_z), the two horizontal components of the magnetic field ($H_{ö}$, H_r) and the return-stroke velocity (RSV), 2 km north of the Tower (see Figure 1). Two 2-dimensional images (taken from directions that are approximately perpendicular to each other) of the lightning flash trajectory have also been recorded using VHS cameras. A typical lightning flash striking the tip of the Tower is shown in Fig. 2.

Since 1996, an expansion of the measuring facilities has been taking place. In the summer of 1996, a 1000-picture/sec High-Speed Camera (HSC) was placed at a station 2 km north of the Tower. In 1997, a noise-protected current measuring system (including a new Rogowski coil and a fiber link) was installed at the Tower. Recently, two double-channel digitizers with higher time resolution and much larger memory were attained for the measurement of the lightning current derivative and its corresponding electromagnetic field. For time synchronization of all measuring instruments, several Global Positioning Systems (GPS) have also been acquired.

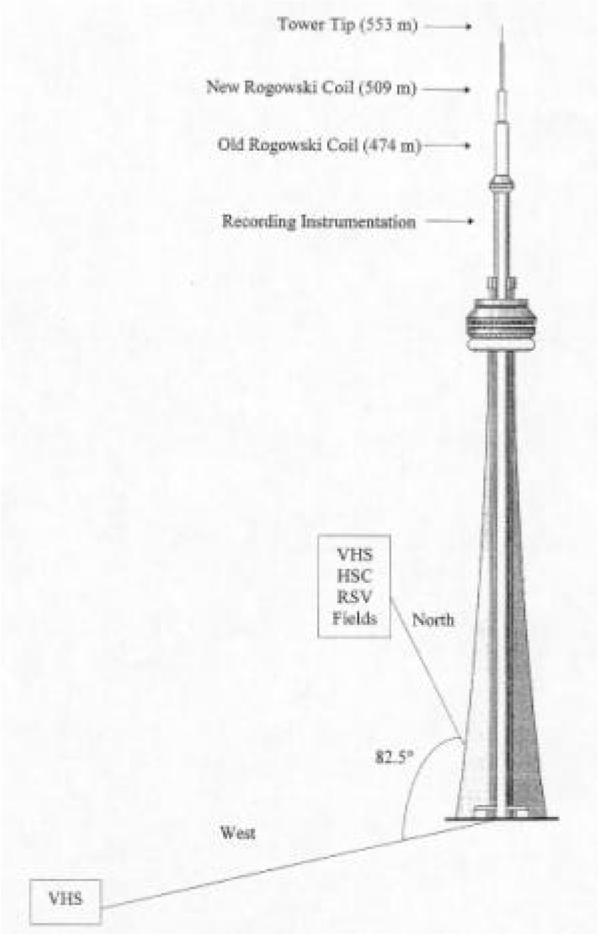

Figure 1. The CN Tower with the locations of measuring systems

Figure 2. A typical trajectory of a lightning flash striking the tip of the CN Tower.

In this paper, extensive statistics of lightning-generated electric and magnetic field waveform parameters (field peak, 10% to 90% risetime to field peak and pulse width at the 50% level of the field peak) are established on the basis of data collected during the last four years (1999-2002). These statistics are relevant to the establishment of more sophisticated procedures for protection from the effects of the lightning-generated electromagnetic pulse (LEMP), especially in the vicinity of tall structures where LEMP increases substantially in magnitude and steepness [10].

II. Field Measuring System

The vertical component of the electric field (E_z) and the two horizontal components of the magnetic field (azimuthal-$H_ö$ and radial-H_r), resulting from strikes to the CN Tower as well as from strokes occurring in its vicinity, have been consistently captured by broadband field sensors since 1991. The sensors were developed at the university of Ottawa, Ontario, Canada [11,12]. They are mounted on a metallic plate, connected through a short low-inductance strap to a conducting cover that exists on the periphery of the 20-m above ground level roof of the Rosebrugh Building of the University of Toronto, 2 km north of the Tower (Fig. 1). Frequency domain calibrations of the sensors were performed in the laboratory using a transverse electromagnetic (TEM) cell. Obtained characteristics are similar to those described in [11,12].

The electric field sensor is an active hollow hemispherically shaped monopole with a sensitivity of 2.38 mV/(V/m). The sensor has low and high 3-dB roll-off frequencies of 47 Hz and 100 MHz, respectively. The azimuthal ($H_ö$) and radial (H_r) magnetic field sensors are of the small loop antenna type with sensitivities of 0.421 V/(A/m) each and with 3-dB frequency bandwidths of 635 Hz to 134 MHz and 697 Hz to 150 MHz, respectively. The circular loops of the magnetic sensors are oriented in mutually perpendicular vertical planes with the CN Tower in the plane of the loop of the $H_ö$ sensor.

The three field sensors are connected via 50-Ù coaxial cables to two 10 bit, 10 ns computer controlled double-channel digitizers with segmented memories (Tektronix 710A). The overall risetime of the field measuring system is estimated to be less than 5 ns. The azimuthal component of the magnetic field ($H_ö$) is captured using two digitizing channels with different scales to enhance the vertical resolution of recorded waveshapes.

III. Observations

Typical CN Tower lightning return-stroke current derivative, current, and electric and magnetic field waveforms are presented in Figs. 3-6. They represent the first of a 3-stroke flash to the Tower recorded on April 8, 1999 at 00:56:33. Only the current derivative signal captured by the new Rogowski coil (Fig. 3) is shown because of its superior signal-to-noise-ratio compared to the noisy current derivative signal captured by the old Rogowski coil [13,14]. The new Rogowski coil is noise protected due to the use of a fiber link. The lightning current waveform, shown in Fig. 4, is obtained by time integration of the current derivative signal presented in Fig. 3. Figures 5 and 6 show, respectively, the vertical component of the electric field (E_z) and the azimuthal component of the magnetic field ($H_ö$) measured 2 km north of the Tower. For CN Tower strokes, the radial component of the magnetic field (H_r) has always been found to be much smaller than $H_ö$, and thus not considered here. Table 1 presents the waveform parameters (peak, 10% to 90% risetime to peak and pulse width at the 50% level of the peak). For the current waveform, the first peak was chosen to represent the true peak [4]. The absolute peak shown in Fig. 4 is not considered in Table 1 because it is a result of current reflection from the ground.

Table 1. Waveform parameters.

	Current Derivative (kA/µs)	Current (kA)	Electric Field (kV/m)	Magnetic Field (A/m)
Peak	25.69	5.19	1.57	1.68
Risetime	333 ns	398.6ns	1.07 µs	1.14 µs
Pulse Width	55.8 ns	-	3.55 µs	1.62 µs

IV. Statistical Analysis

Figures 7-12 present the cumulative statistics of electric and magnetic field waveform parameters (field peak, 10% to 90% risetime to field peak and pulse width at the 50% level of the field peak), which are established on the basis of data collected during the last four years (1999-2002). These collected data represent fields generated by 62 flashes to the CN Tower containing 152 strokes.

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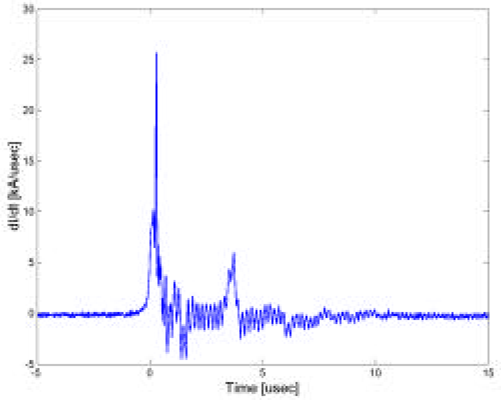

Figure 3. The current derivative signal captured by the new coil (April 8, 1999 at 00:56:33).

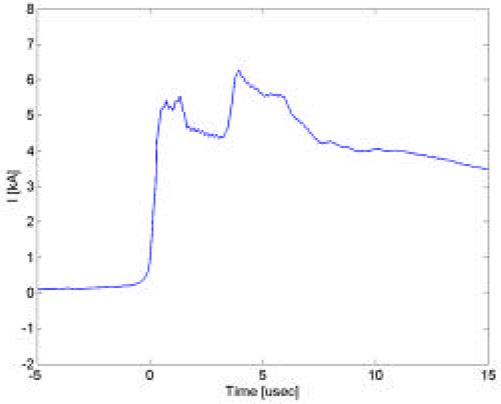

Figure 4. Current waveform (time integral of the current derivative signal shown in Figure 3).

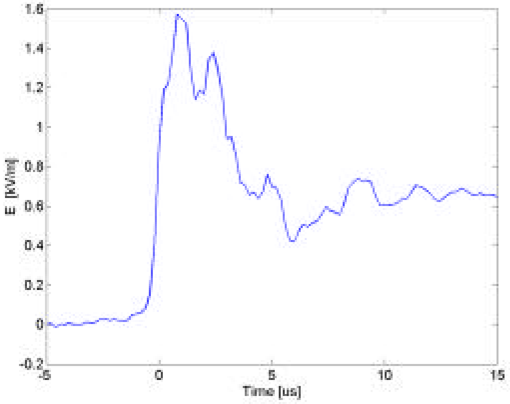

Figure 5. The vertical component of the electric field generated by a lightning stroke to the CN Tower (April 8, 1999 at 00:56:33).

It is worth mentioning that the number of confirmed flashes to the Tower during these years is substantially more than 62, but in many cases the lightning-generated electromagnetic field was not successfully measured.

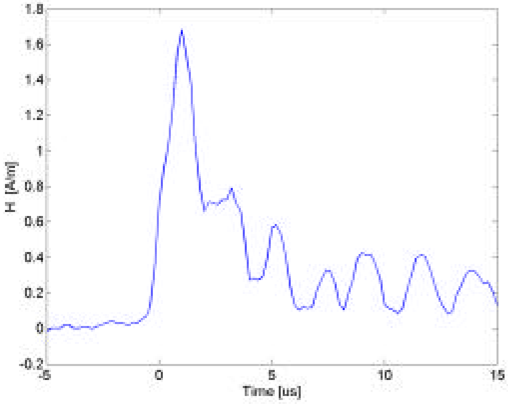

Figure 6. The azimuthal component of the magnetic field generated by a lightning stroke to the CN Tower (April 8, 1999 at 00:56:33).

The statistical analysis shows that in 50% of the electric field records, the peak exceeds 812 V/m, the risetime exceeds 1 ìs and the pulse width exceeds 2 ìs. In 50% of the magnetic field records, the peak exceeds 1.21 A/m, the risetime exceeds 1.17 ìs and the pulse width exceeds 1.59 ìs.

Tables 2 and 3 summarize the statistical analysis which can be extracted from Figs. 7-12. Table 2, for example, indicates that the CN Tower lightning-generated electric field peak, during the last four years, ranged from 240 V/m to 3.24 kV/m with an average of 970 V/m. The electric field peak exceeded 380 V/m in most cases (95% probability), while it rarely (5% probability) exceeded 3.22 kV/m. Tables 2 and 3 show that the range of variation of the electric or the magnetic field peak substantially exceeded one order of magnitude. Therefore, the use of digitizers with 10 bit vertical resolution is highly recommended for the measurement of LEMP. The tables also show that the minimum risetime measured was 200 ns. Thus, the time resolution used to capture the field signals (10 ns) is appropriate. The use of digitizers with better time resolution is not needed.

V. Concluding Remarks

This paper has presented the cumulative statistics of the waveform parameters of the electromagnetic pulse (electric and magnetic field peaks, risetimes to field peaks and pulse width at the 50% level of the field peaks) generated by lightning to the CN Tower during the last four years. It was found that in 50% of the recorded electric field waveforms, the peak exceeds 812 V/m, the risetime exceeds 1 ìs and the pulse width exceeds 2 ìs. In 50% of the magnetic field records, the peak exceeds 1.21 A/m, the risetime exceeds 1.17 ìs and the pulse width exceeds 1.59 ìs. The range of variation of either the electric or the magnetic field peaks was found to substantially exceed one order of magnitude. Therefore, the use of digitizers with 10 bit vertical resolution is highly recommended for the measurement of LEMP.

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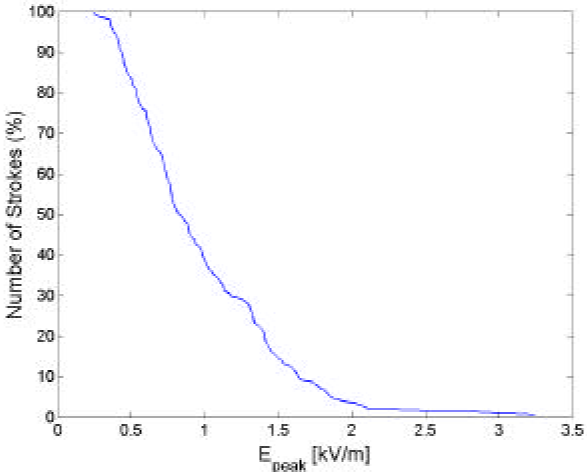

Figure 7. Cumulative distribution of E_z peak.

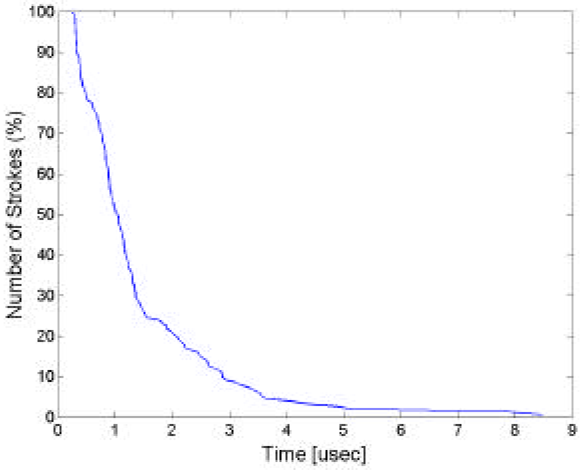

Figure 8. Cumulative distribution of E_z risetime.

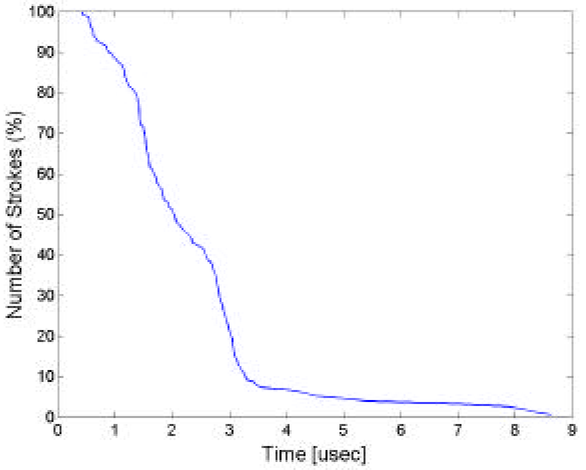

Figure 9. Cumulative distribution of E_z pulse width.

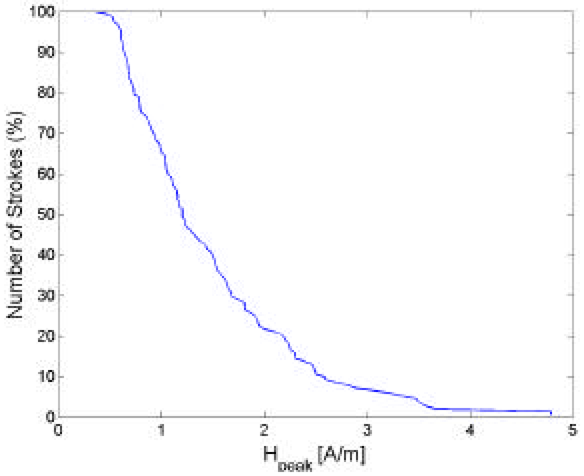

Figure 10. Cumulative distribution of $H_{\ddot{o}}$ peak.

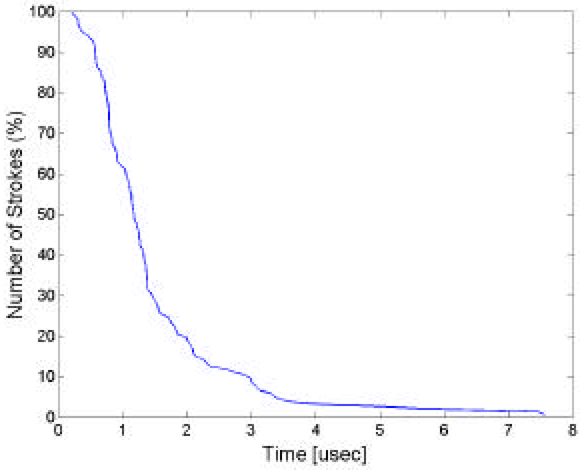

Figure 11. Cumulative distribution of $H_{\ddot{o}}$ risetime.

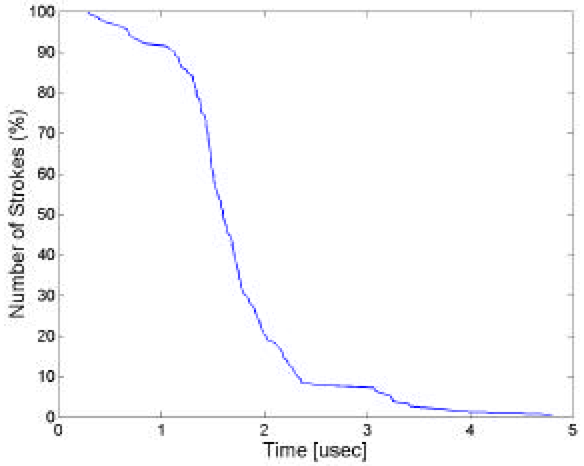

Figure 12. Cumulative distribution of $H_{\ddot{o}}$ pulse width.

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The minimum measured risetime during the last four years was 200 ns. Thus, the 10 ns time resolution used to capture the field signals proved to be appropriate.

The presented statistical results will assist in the evaluation of the risk posed by the lightning-generated electromagnetic pulse (LEMP) to sensitive electronic devices and circuits. This leads to the establishment of more sophisticated protective measures against interference due to LEMPs, especially those generated from lightning occurring at elevated objects.

Acknowledgement

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Table 2. Electric field waveform parameters.

E_z	Min.	95%	50%	Avg.	5%	Max.
Peak (kV/m)	0.24	0.38	0.81	0.97	1.84	3.24
Risetime (ì sec)	0.23	0.31	1.01	1.39	3.56	8.47
50% Pulse Width (ì sec)	0.42	0.61	2.02	2.29	4.46	8.63

Table 3. Magnetic field waveform parameters.

$H_{ö}$	Min.	95%	50%	Avg.	5%	Max.
Peak (A/m)	0.35	0.60	1.21	1.47	3.22	4.79
Risetime (ì sec)	0.20	0.34	1.17	1.44	3.29	7.56
50% Pulse Width (ì sec)	0.29	0.67	1.59	1.70	3.14	4.79

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