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Luminosity Characteristics of CN Tower Lightning Flash Components

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***Abstract*— In 1991, simultaneous measurements of all relevant CN Tower lightning parameters commenced, including the current derivative at the tower, the corresponding lightning-generated electric and magnetic fields, 2 km north of the tower, and the optical channel characteristics. The paper presents recent results comprising twenty-nine flashes that struck the tower within the past five years (2013-2017), based on the records of Phantom v5.0 high-speed camera, operating at 1 ms resolution. The number of recorded CN Tower flashes in the past five years can be classified as: seven flashes in 2013; seventeen flashes in 2014, out of which thirteen struck the tower on Sept. 5, 2014 within 111.4 min, resulting in, on average, a flash to the tower every 9 min and 17 s; the years 2015-2017 produced four flashes to the tower each year. The emphasis of this study is to perform statistical analyses of various lightning flash components, which are pivotal for protection of tall structures against lightning hazards. The acquisition of the data from Phantom v5.0 high-speed camera provides the required details regarding different flash components such as the initial continuous current duration, flash multiplicity, inter stroke time, flash duration and continuing current duration.**

Keywords—Lightning Initiated from Tall Structures, Luminosity variation with time, Flash duration, Initial Stage Current duration, Flash multiplicity, Interstroke Time, Continuing Current Duration.

I. INTRODUCTION

The Canadian National (CN) Tower is 533.3 m high, one of the tallest free-standing structure in the world located at 43.64° N and 79.38° W, in downtown Toronto, Ontario, Canada. The CN Tower usually receives several dozens of lightning flashes yearly, due to its tall altitude. However, the lightning ground flash density in Toronto is about two [Hussein et al., 2010a]. A grounded tall structure produces relatively large electric field enhancement near their upper extremities so that upward leaders are initiated earlier from these structures as compared to short objects in its vicinity and, therefore, serve to make the tall structure a preferential lightning termination point. Structures with altitudes greater than 500m experience upward flashes [Rakov 2003]. Also, lightning is been triggered artificially using "rocket-and-wire" technique. Rocket-triggered lightning is also initiated by an upward leader propagating from the tip of small rocket trailing a thin grounded conducting wire towards a charged cloud. However, it has been observed that initial-stage current (ISC) pulses in object-initiated lightning exhibit larger peaks, shorter risetimes and shorter half-peak widths, when compared with ISC pulses in rocket-triggered lightning [Miki et al., 2005]. Thus, it is prominent that CN Tower is an ideal site, well equipped with lightning measurement systems to facilitate the research of lightning, that assists to comprehend the physics of lightning as well as determining the statistical analysis based on optical characteristics [Hussein et al., 2010b], the lightning current [Hussein et al., 2001] and its generated electromagnetic pulses [Rachidi et al., 2001; Hussein et al., 2008]. Moreover, the lightning return stroke current models have been developed [M. Milewski et al., 2009] and the performance characteristics of North American Lightning Detection Network (NALDN) have been evaluated based on CN Tower Lightning Data [Kazazi et al., 2015].

Lightning Strikes to the CN Tower have been comprehensively observed since 1990. Present instrumentation allows the recording of the lightning current derivative using two current measurement systems: a new Rogowski Coil installed at 509 m Above Ground Level (AGL), connected by a fibre link to LeCroy LT342L digitizer; an old Rogowski Coil was previously installed at 474m, connected to a National Instrument (NI) PCI-5114 digitizer through a tri-axial cable [Fig-1]. Simultaneously, the CN Tower lightning channel trajectories are recorded by: a Sony HDR PJ790VB low-speed camera, operating at 60 frames per Second (fps) with 16.67ms time resolution and 1920x1080 frame resolution; a Phantom v5.0 digital high-speed camera operating at 1000 fps and frame resolution of 512x512 with a recording time of 1300 ms. Five global positioning systems (GPS) are acquired for time synchronization of CN Tower lightning recording systems.

Fig.-1: The CN Tower and Location of Instruments

II. HIGH-SPEED IMAGINING DIGITAL IMAGE RECORDING SYSTEM

In 2006, a Phantom v5.0 high-speed camera (HSC) [Fig.-2] was installed at 4.73 Km North-East of the CN Tower. It has a pixel resolution of 1024x1024, however it is set to operate at 512x512 for allowing longer recording time of 1300 ms, including 300ms pre-triggering time to record ISC and 1s to record the remaining flash components. The exposure time of HSC is 10 µs and it is triggered by an infrared sensor and it has SR-CMOS anti-blooming sensors. It has 1024 MB internal storage, which allows the continuous recording 1024 images per second at 1000 fps. The recorded data is saved in separate files with extension .cine and it can be converted to a suitable format for data analysis using MATLAB.

Phantom v5.0 HSC provides detailed information regarding all flash components, such as: the initial-stage current (ISC), return strokes (RSs), M-components, continuing current (CC) and flash initiation direction.

A. *Analysis of Recorded HSC Data*

The analysis of HSC records of CN Tower lightning flashes is based on the study of lightning channel maximum and average luminosity variation along successive frames within each flash [Hussein et al., 2006]. Phantom v5.0 HSC comprises luminosity saturation at the 255 level, which implies that the variation of maximum luminosity beyond such level is not recorded. In order to resolve this problem, the average luminosity time variation across the width of the channel is determined.

Fig. 3 illustrates the channel trajectory of a CN Tower flash, recorded by HSC on July 8, 2013. The time variation of maximum and average luminosity is evaluated along a horizontal pixel line y = 322 over 1300 frames and is demonstrated in Fig. 4 and Fig. 5 respectively.

Fig.-2: Phantom v5.0 high speed camera

The luminosity variation with time [Figs. 4, 5] illustrates a flash starting with ISC of 200 ms duration, containing several M-components and followed by a single return stroke.

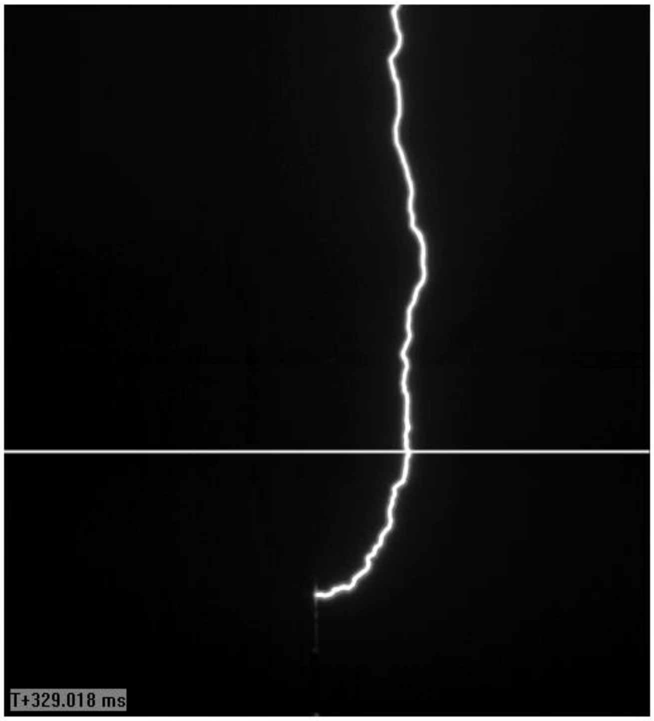

Fig. 3: Channel trajectory image record of the flash captured on July 8, 2013. This flash struck the CN Tower 17 m below its tip.

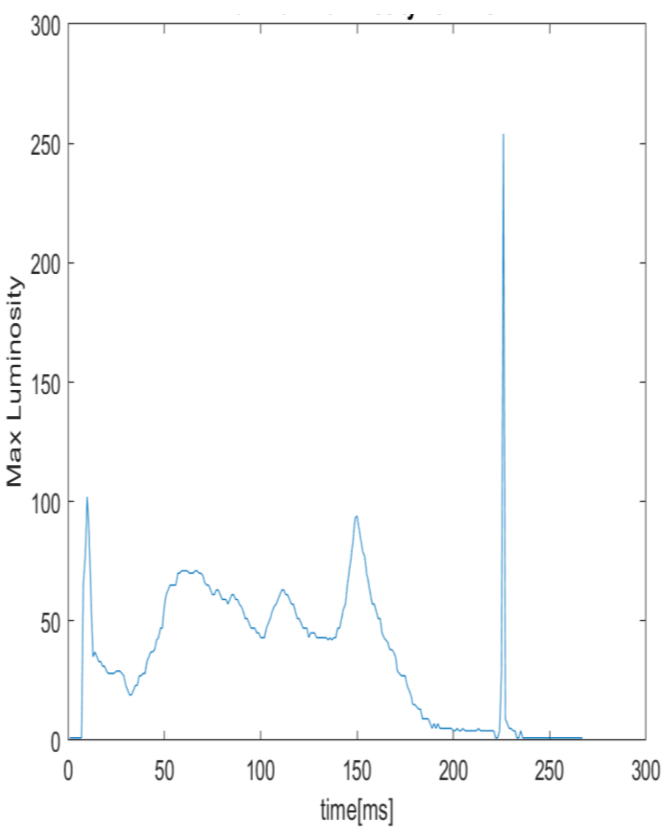

Fig. 4: Maximum channel luminosity variation with time the along horizontal pixel line y=322

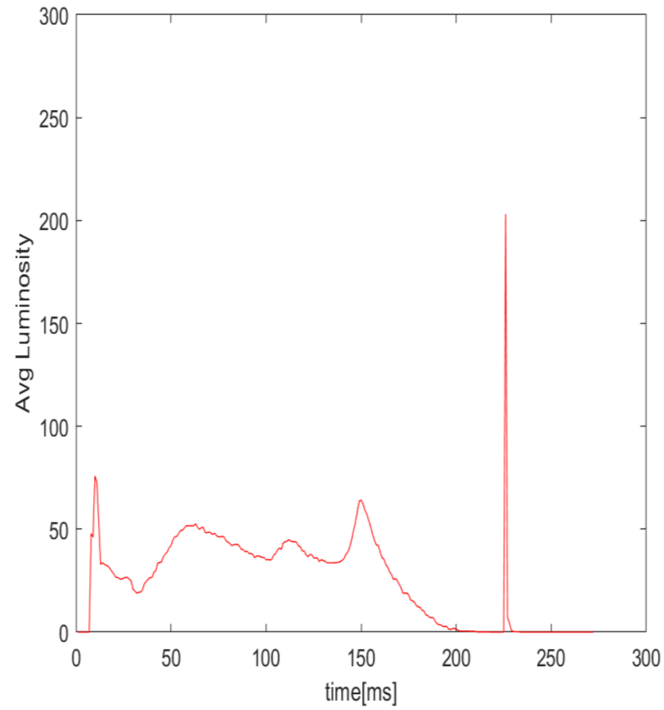

Fig. 5: Average channel luminosity variation with time along horizontal pixel line y=322 across a 11-pixel wide channel.

Fig. 6 illustrates the channel trajectory image of another CN Tower flash, recorded by HSC on July 08, 2013.

The luminosity variation with time [Figs. 7, 8] reveals the existence of an ISC of duration 167 ms, comprising several M-components.

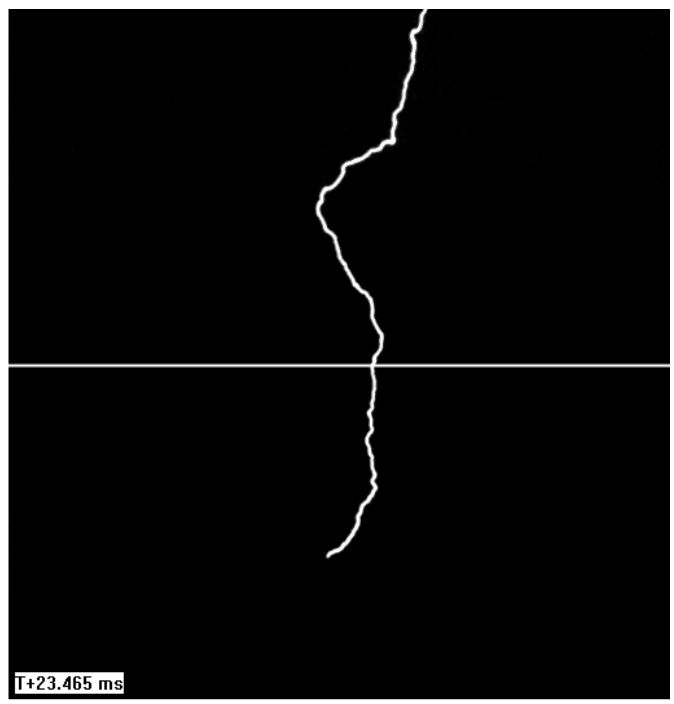

Fig. 6: Channel trajectory image record of another flash captured on July 8, 2013.

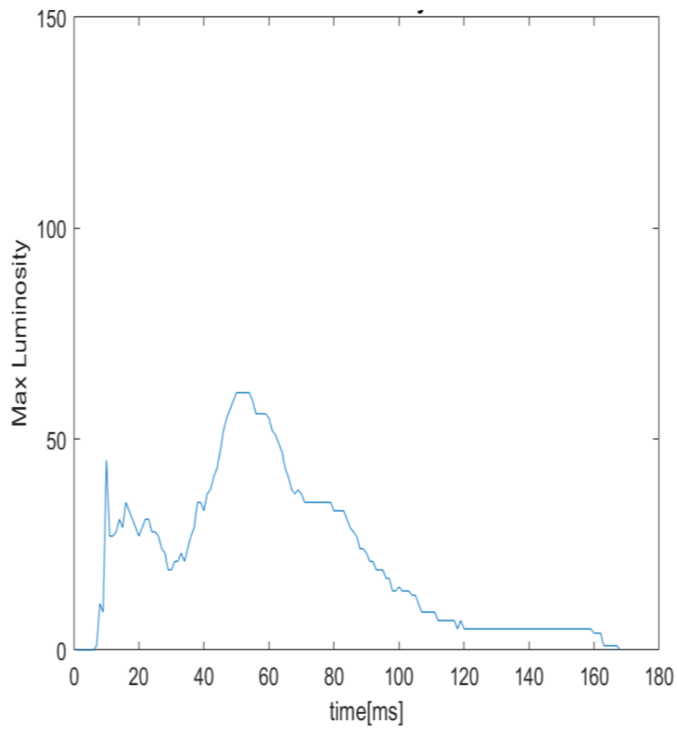

Fig. 7: Maximum channel luminosity variation with time along horizontal pixel line y = 265

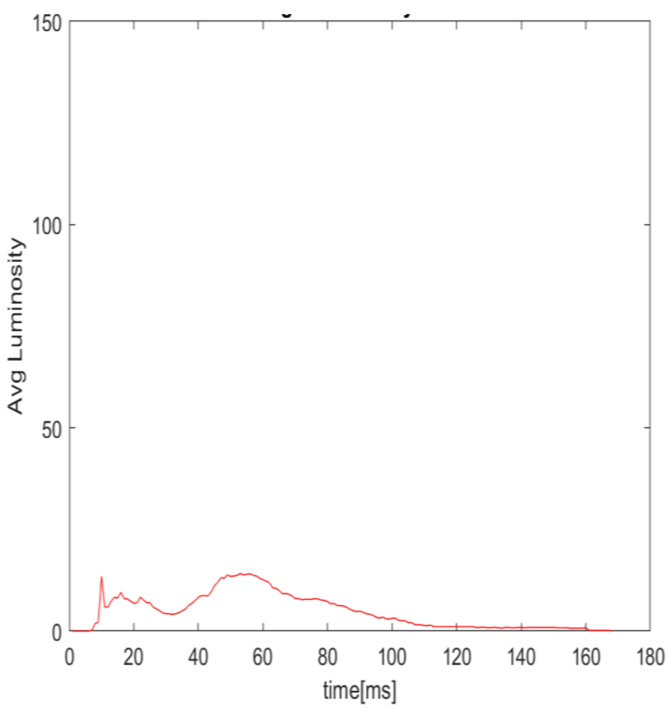

Fig. 8: Average channel luminosity variation with time along the horizontal pixel line y = 265 across a nine-pixel wide channel

Fig. 9 depicts the channel trajectory of the fifth CN Tower flash, recorded by HSC on September 05, 2014 storm.

The luminosity variation with time [Figs. 10, 11] illustrates that the flash contains ISC with duration of 591 ms, with several M-components superimposed on it and followed by two return strokes; each return stroke is followed by continuing currents.

Fig. 9: Channel trajectory image record of a fifth flash captured on September 05, 2014.

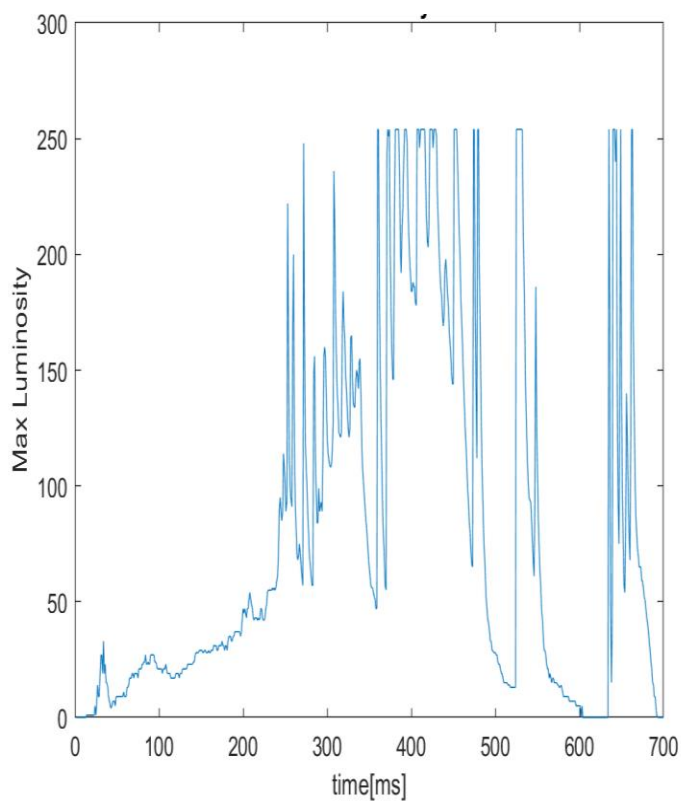

Fig. 10: Maximum channel luminosity variation with time along the horizontal pixel line y = 261

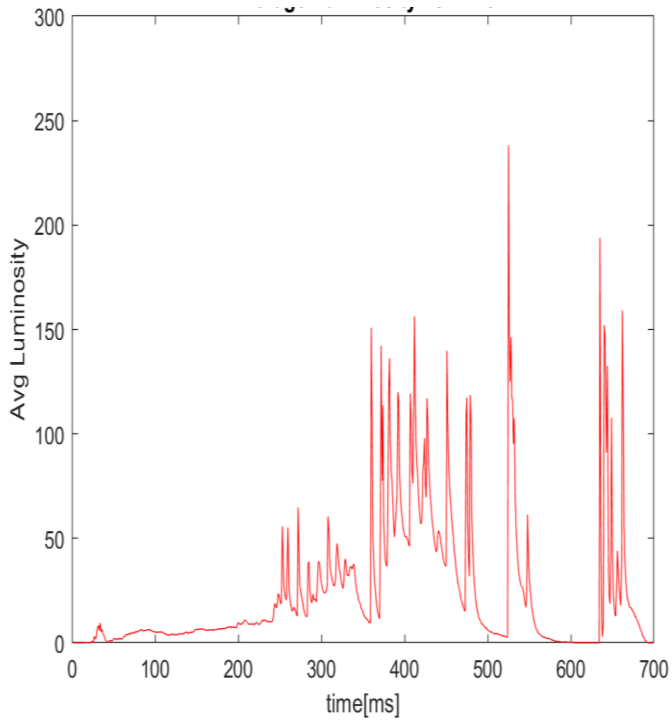

Fig. 11: Average channel luminosity variation with time along horizontal the pixel line y = 261 across a fifteen-pixel wide channel.

Fig. 12 illustrates the channel trajectory of another CN Tower flash, recorded by HSC during September 05, 2014 storm.

The luminosity variation with time [Figs. 13, 14] demonstrates that a flash comprises only ISC of duration 293 ms, with several M-components superimposed on it.

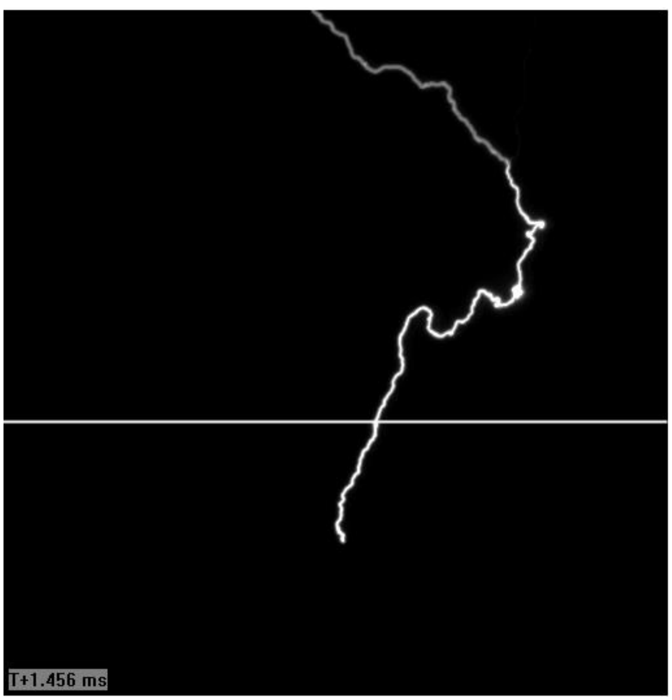

Fig. 12: Channel trajectory image record of a tenth flash captured on September 05, 2014.

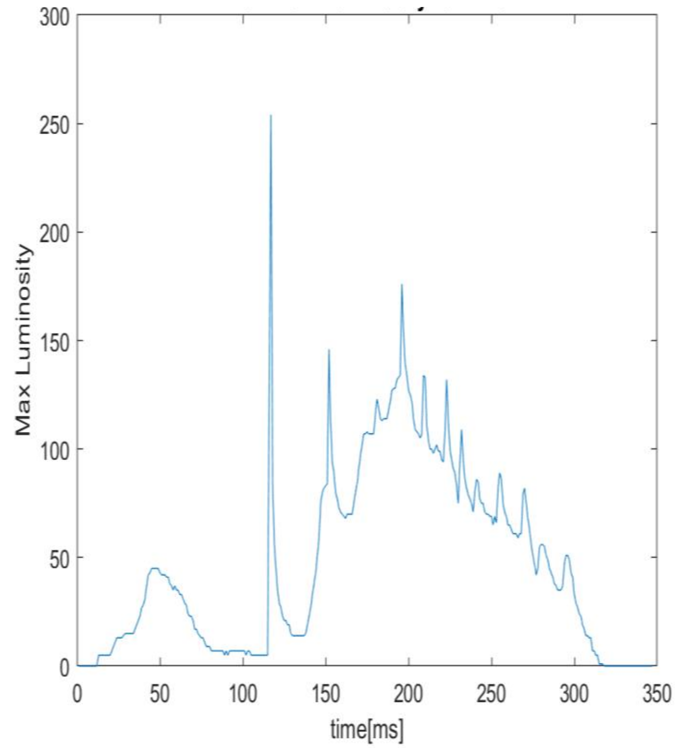

Fig. 13: Maximum channel luminosity variation with time along the horizontal pixel line y = 308

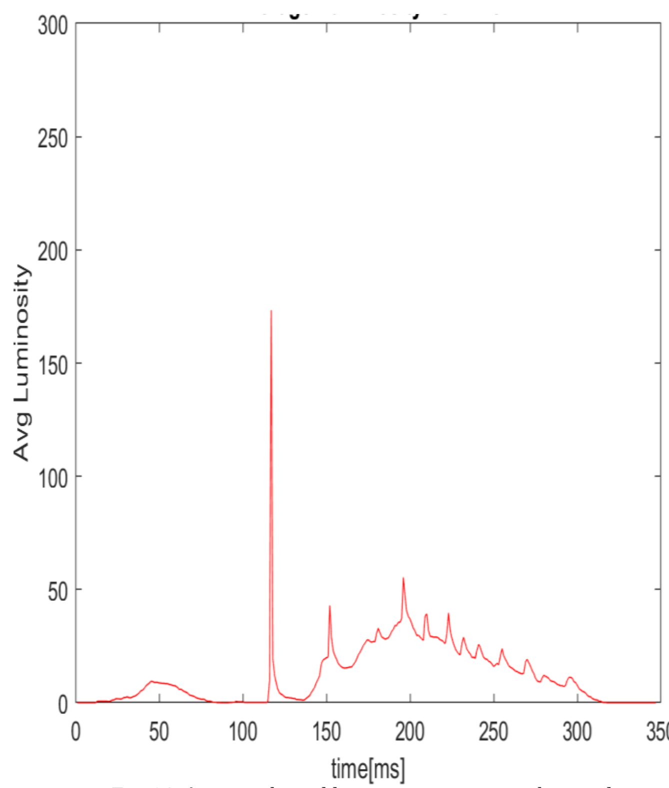

Fig. 14: Average channel luminosity variation with time along the horizontal pixel line y = 308, across an eight-pixel wide channel.

Fig. 15: presents the channel trajectory of a second CN Tower flash, recorded by HSC during September 07, 2016.

The luminosity variation with respect to time [Figs. 16, 17] demonstrates that this flash doesn't contain ISC. The flash begins with a return stroke, followed by a continuing current with M-components, that persists for 218 ms.

Fig. 15: Channel trajectory image of a flash recorded on September 07, 2016.

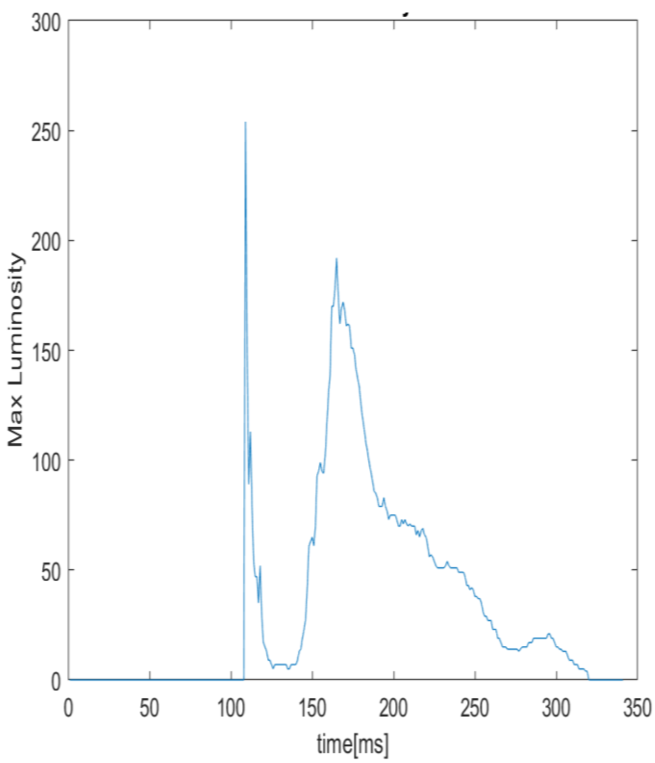

Fig. 16: Maximum channel luminosity variation with time along the horizontal pixel line y = 257

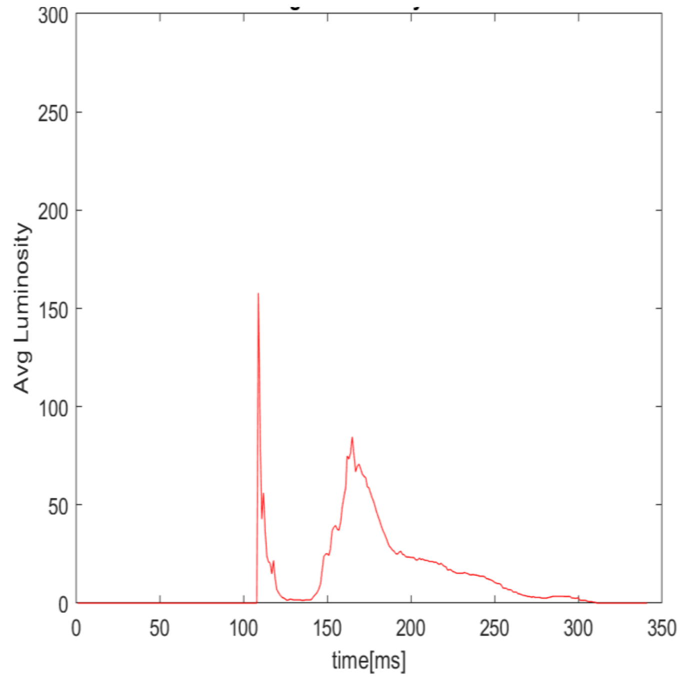

Fig. 17: Average channel luminosity variation with time along the horizontal pixel line y = 257, across a ten-pixel wide channel.

Fig. 18 represents the channel trajectory of a first CN Tower flash, recorded by an HSC on September 04, 2017.

Figs. 19 and 20 reveal that the flash doesn't contain ISC. The flash comprises two return strokes; each is followed by a continuing current with M-components superimposed on it. The continuing current following the first return stroke is prolonged for 142 ms and the continuing current following second return stroke lasted for 84 ms.

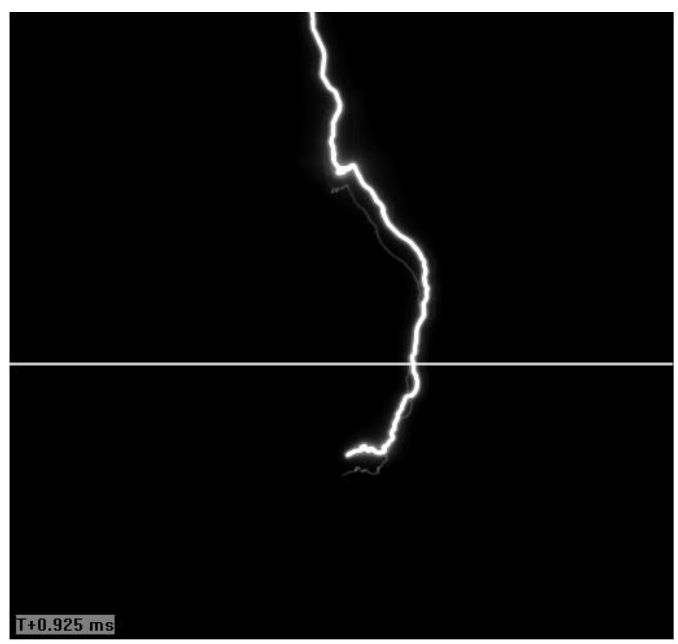

Fig. 18: Channel trajectory image record of a first flash captured on September 04, 2017.

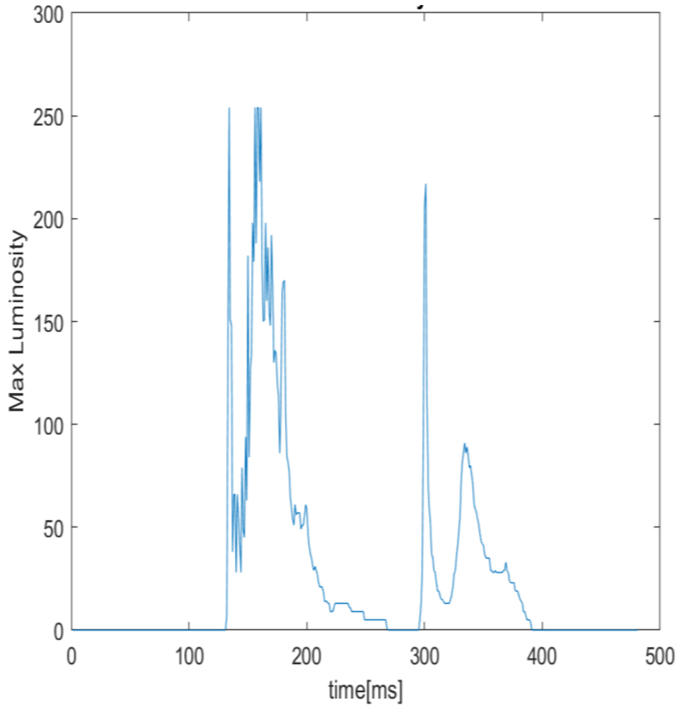

Fig. 19: Maximum channel luminosity variation with time along horizontal pixel line y = 288

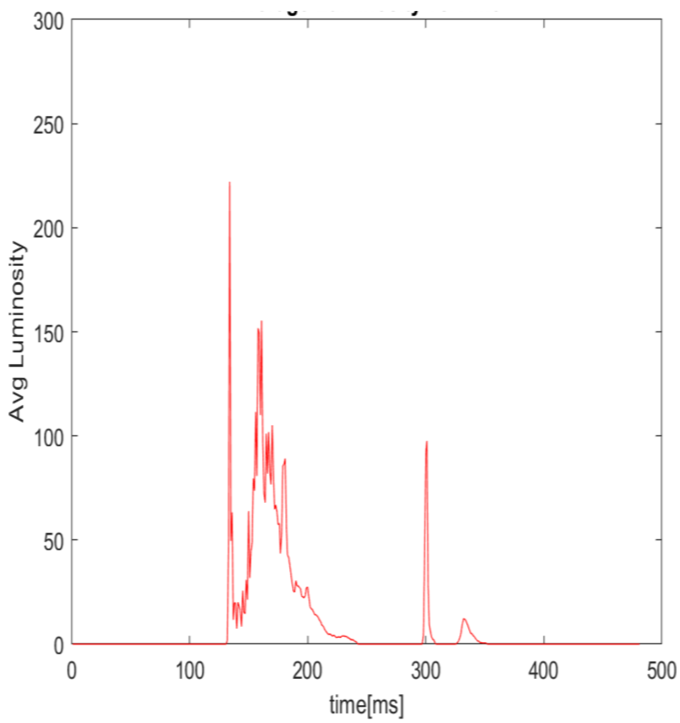

Fig. 20: Average channel luminosity variation with time along the horizontal pixel line y = 288, across an eight-pixel wide channel.

III. CHARACTERIZATION OF FLASH COMPONENTS

The statistical analysis of lightning flash characteristics presented in this paper are based on Phantom v5.0 HSC records within the past five years (2013-2017). It was observed that a total of 29 flashes struck within this period. It is worth mentioning that 13 flashes were recorded during a storm of September 05, 2014, the storm lasted for 111.4 minutes. It is important to emphasis that only 14 out of total 29 CN Tower flashes contained RSs, with an average multiplicity of 2.57. It was noted that 10 out of 29 flashes were proved to be upward initiated, based on upward leader initiating flashes. While, one out of 29 flashes hit the tower below its tip, at the distance of 17 m. It was also observed that 7 out of 29 flashes did not exhibit ISC (24.137%). Furthermore, it was also noticed that out of 14 flashes (containing return strokes), 12 flashes comprised continuing current (85%).

The statistical analyses of flash components, namely flash duration, duration of initial stage current (ISC), flash multiplicity, inter stroke time (IST) and duration of continuing current (CC) have been derived based on video records of Phantom v5.0 HSC.

A. *Flash Duration*

The 13 flashes received on September 05, 2014 storm contains an average flash duration of 386.23 ms. For all 29 flashes recorded, the average flash duration is 306.62ms. Fig. 21 illustrates the frequency distribution of flash durations for 29 flashes based on HSC video records. The figure shows that 79% of flashes contains flash duration within the range of 50 ms to 400 ms and 55% of flashes have flash duration within the range of 150 ms to 300 ms.

Fig. 22 demonstrates the cumulative probability distribution of flash duration for the all 29 flashes (solid red line), 14 flashes containing RSs (green dashed line) and 15 flashes without RSs (blue dotted line). The statistics show that the flashes comprising ISC and RSs have statistically longer flash duration as compared to the flashes constituting only RSs. Table I. demonstrates a summary of (2013-2017) characteristics of flash duration.

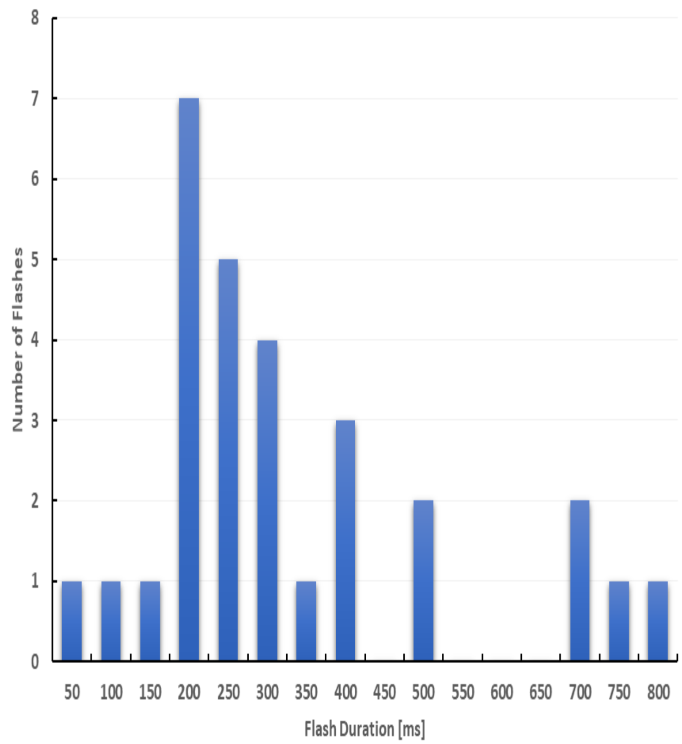

Fig. 21: Frequency Distribution of Flash Duration, 2013-2017

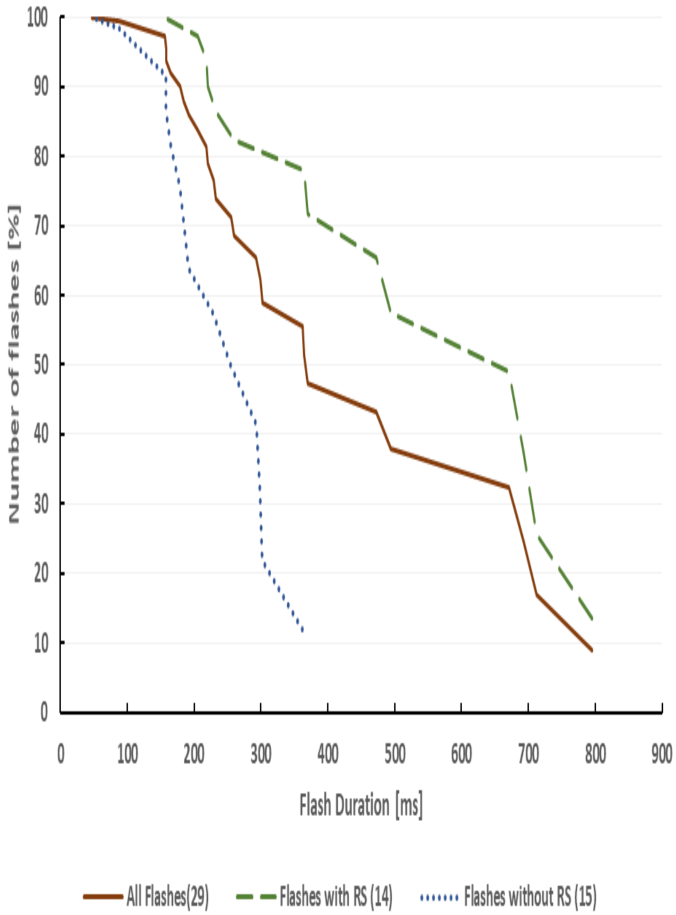

Fig. 22: Cumulative Probability Distribution of Flash Duration, 2013-2017

TABLE I. Summary of Flash Duration Statistics

	Flash Duration [ms]		
	All (29)	ISC&RSs (14)	ISC only (15)
Minimum	47	156	47
Maximum	795	795	362
Mean	306.62	418.714	202
Standard Deviation	194.919	212.95	84.48

B. Initial Stage Current Duration

The average ISC duration exhibited by the 13 flashes of September 05, 2014 storm is 335.58 ms. Whereas, the 29 flashes received on 2013-2017 period comprised of average ISC duration of 260.954 ms.

Figs. 23 and 24 illustrate the frequency distribution and the cumulative probability distribution of ISC duration respectively. The frequency distribution for the period of last five years represents that 86% of flashes comprises the ISC of duration within the range of 45 ms to 450 ms, whereas 13% of flashes exhibits the ISC duration within the 550 to 650 ms range.

Fig. 24 presents the cumulative probability of ISC duration for all 29 flashes (solid red line), 7 flashes with RSs (green dashed line) and 15 flashes without RSs (blue dotted line). The figure represents that ISC's without return strokes have a lower duration for ISC as compared to the ISC's with return strokes.

Table II. depicts a summary of (2013-2017) characteristics of ISC duration.

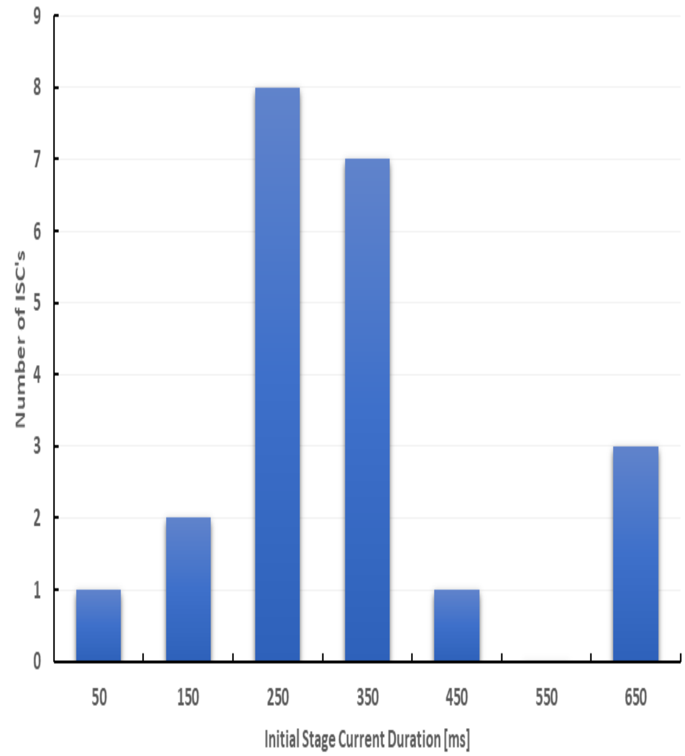

Fig. 23: Frequency Distribution of Initial Stage Current Duration, 2013-2017

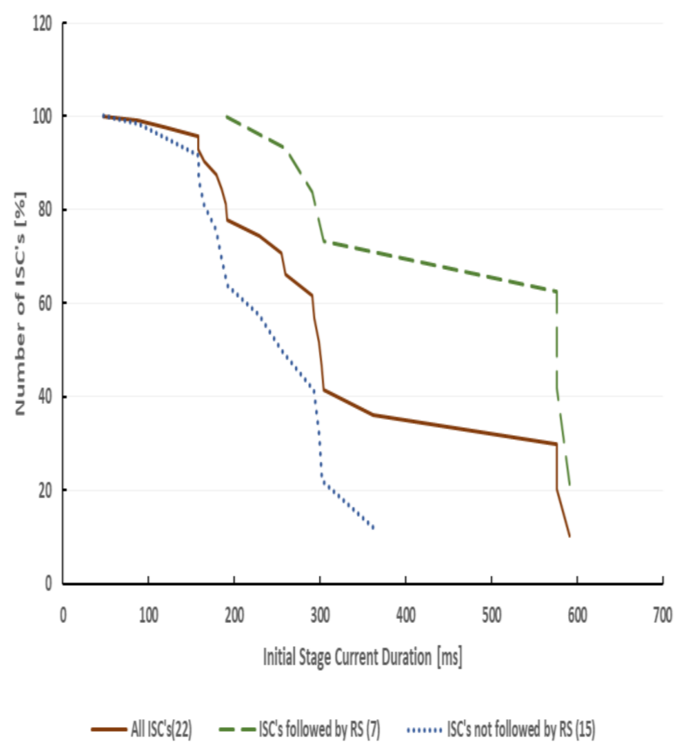

Fig. 24: Cumulative Probability Distribution of Initial Stage Current Duration, 2013-2017

TABLE II. Summary of Initial Stage Current Statistics

Initial Stage Current[ms]			
	All (22)	ISC&RSs (7)	ISC only (15)
Minimum	47	190	47
Maximum	576	591	362
Mean	264.45	398.28	202
Standard Deviation	146.808	161.78	84.48

C. *Flash Multiplicity*

The number of return strokes varied between 1 to 9 for the period 2013-2017. The storm that occurred in 2014, that led to 13 CN Tower flashes contained 21 return strokes and the number of return stroke per flash varied between 1 to 7.

Figs. 25 and 26 illustrate the frequency distribution and cumulative probability distributions for a flash multiplicity of last five-year flashes respectively. The frequency distribution for the flash multiplicity of the 2013-2017 flashes demonstrates that 85% of flashes contained the number return strokes within the range of 1 to 4, whereas 14% of flashes comprised the number of return strokes within the range of 7 and 9.

Fig. 26 demonstrates the cumulative probability distribution for a flash multiplicity of all 14 flashes (solid red line), 7 flashes with ISC (green dashed line) and 7 flashes without ISC (blue dotted line). The figure depicts that the flashes without ISC contained a greater number of return strokes compared to the flashes containing ISC. Table III. presents a summary of 2013-2017 characteristics of flash multiplicity.

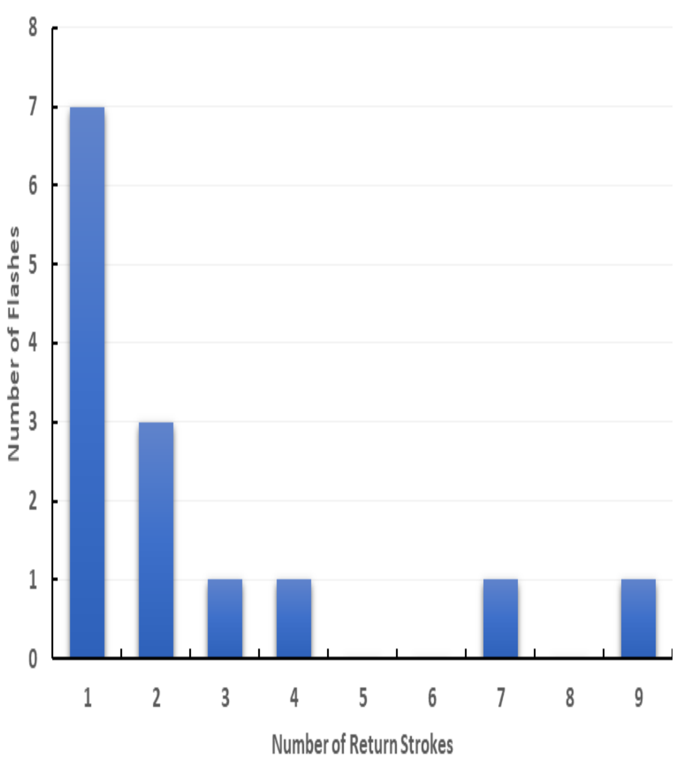

Fig. 25: Frequency Distribution of Flash Multiplicity, 2013-2017

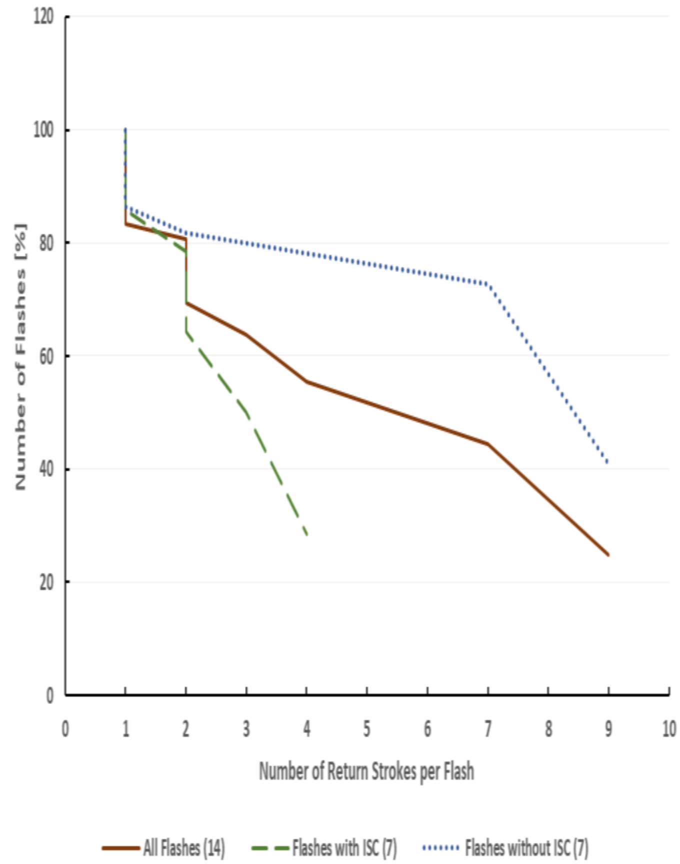

Fig. 26: Cumulative Probability Distribution of Flash Multiplicity, 2013-2017

TABLE III. Summary of Flash Multiplicity Statistics

Flash Multiplicity			
	All (14)	ISC&RSs (7)	RSs only (7)
Minimum	1	1	1
Maximum	9	4	9
Mean	2.57	2	3.14
Standard Deviation	2.4	1.06	3.13

D. *Inter-stroke Time*

The 13 flashes received on September 05, 2014 comprised average inter-stroke time if 62.64 ms, while the 29 flashes received in last five years constituted an average inter-stroke time of 67.67 ms.

Figs. 27 and 28 illustrate the frequency distribution and cumulative probability distribution of inter-stroke time of 2013-2017 CN Tower flashes containing multiple strokes respectively. The frequency distribution for inter-stroke time exhibits that 95% of flashes contains the inter-stroke time within the range of 1 ms to 180 ms, while 5% of flashes constitutes the inter-stroke time within the range of 360 ms to 420 ms. Figure 28 presents the cumulative probability distribution for IST of all 22 flashes (solid red line), 7 flashes with ISC (green dashed line) and 15 flashes without ISC (blue dotted line). The figure depicts that the flashes with RSs only comprised larger IST duration as compared to the flashes containing ISC and RSs. Table IV. illustrates a summary of 2013-2017 characteristics of Inter-stroke Time.

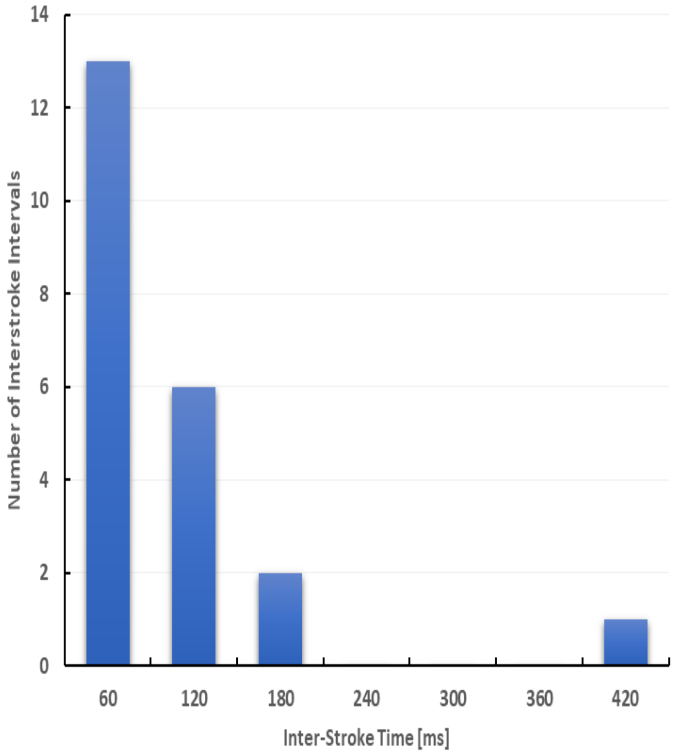

Fig. 27: Frequency Distribution of Inter-stroke Time, 2013-2017

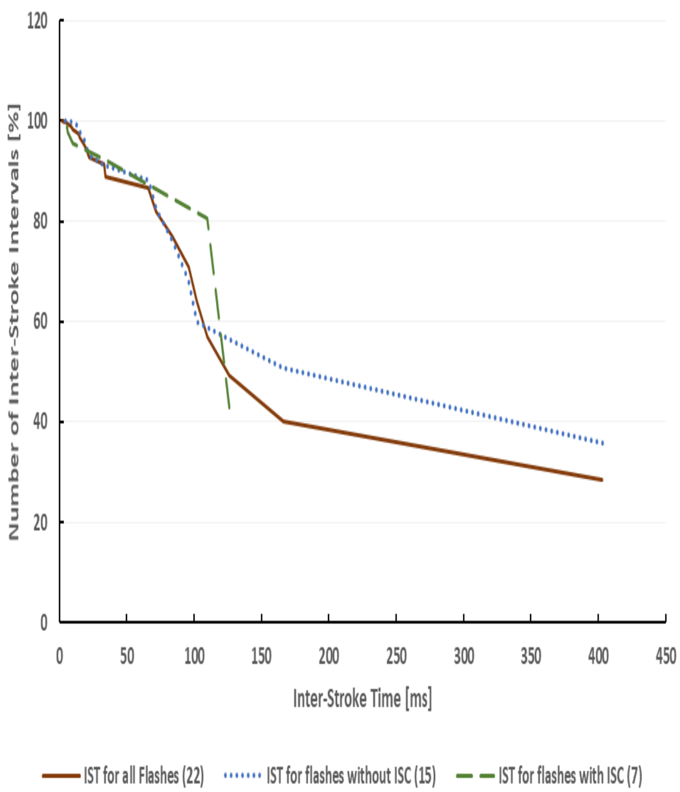

Fig. 28: Cumulative Probability Distribution of Inter-stroke Time, 2013-2017

TABLE IV. Summary of Inter-Stroke Statistics

	Inter-Stroke Time[ms]		
	All (22)	ISC&RSs (7)	RSs only (15)
Minimum	2	2	2
Maximum	403	126	403
Mean	64.318	41.85	74.8
Standard Deviation	87.19	49.32	98.339

E. Continuing Current Duration

The September 05, 2014 storm received 13 flashes with average continuing current duration of 70 ms, whereas the 29 flashes received in last five years constituted an average continuing current duration of 112.95 ms.

Figs. 29 and 30 demonstrate the frequency distribution of the CC duration of 2013-2017 CN Tower flashes. The frequency distribution for CC time duration indicates that 95% of flashes contains CC duration of 1 ms to 300 ms. While, 5% of flashes comprises the CC duration within the range of 500 ms to 550 ms. Fig. 30 illustrates the cumulative probability distribution for CC duration of all 12 flashes (solid red line), 6 flashes with ISC and RSs (green dotted line) and 6 flashes without ISC and comprising only RSs (blue dotted line). The figure depicts that flashes without ISC and containing only RSs constituted larger CC duration as compared to flashes containing ISC and RSs. Table V. depicts a summary of 2013-2017 characteristics of Continuing Current Duration.

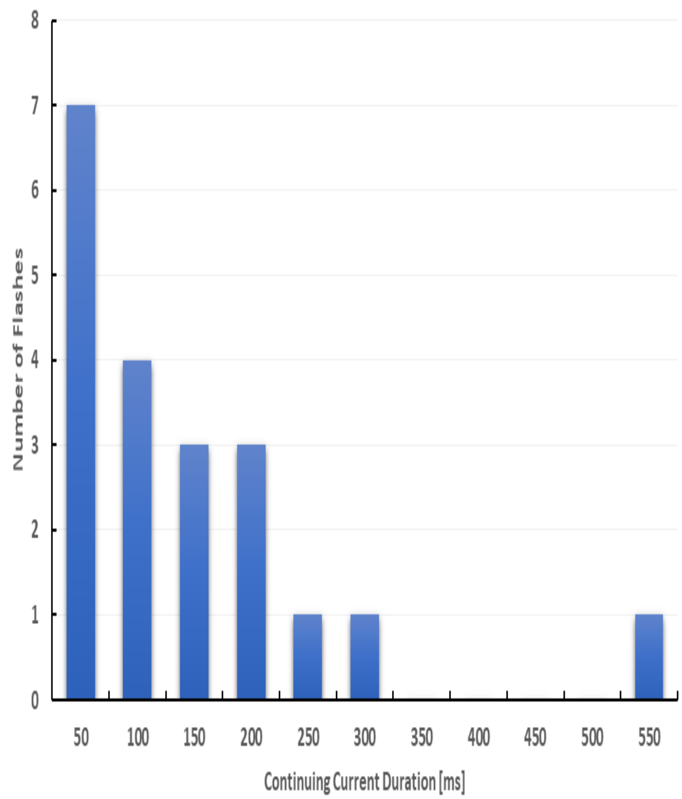

Fig. 29: Frequency Distribution of Continuing Current Time Duration, 2013-2017

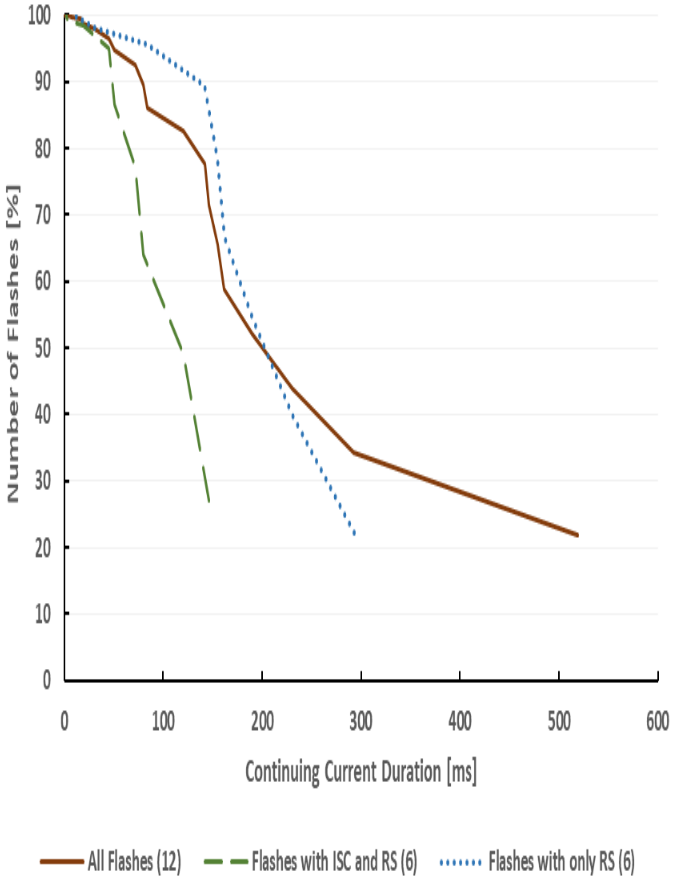

Fig. 30: Cumulative Probability Distribution of Continuing Current Time Duration, 2013-2017

TABLE V. Summary of Continuing Current Statistics

	Continuing Current Duration [ms]		
	All (12)	ISC&RSs (6)	RSs only (6)
Minimum	1	2	8
Maximum	519	146	293
Mean	118.45	54.1	131.3
Standard Deviation	121.38	131.3	90.39

IV. CONCLUSION

In this paper, the statistical analyses of the CN Tower lightning flash characteristics, based on video records of Phantom v5.0 high-speed camera acquired during the past five years (2013-2017), were conducted. The existence of lightning flash components namely, the initial stage current, return strokes, M-components and continuing currents were determined by analyzing video records.

It has been inferred that during the past five years, 15 out of 29 flashes contained ISCs with duration ranging from 47 ms to 190 ms. Also, 14 out of 29 flashes contained return strokes ranging from 1 to 9 with an average flash multiplicity of 2.57. Out of 14 flashes containing return strokes, 50% of these flashes contained ISCs. It was observed that one out of the 29 flashes struck the CN Tower below its tip at a distance of 17 m.

Based on the analysis of video records, the flash time duration varied between 47 ms to 220 ms, with an overall average of 306.62 ms. It was determined from statistical analysis that flashes with ISCs and return strokes were on average 70.67% longer than the flashes containing only ISCs. Also, the ISC duration ranges from 47 ms to 591 ms, with an overall average of 264.45 ms. Also, by analyzing the video records and statistics of ISC durations, it was noted that the flashes with ISCs and return strokes contains ISC duration on average is 74% longer than that ISC duration for flashes containing ISCs not followed by return strokes. Furthermore, flashes with ISCs have an average multiplicity of 2 and flashes without ISC have an average multiplicity of 3.14. Moreover, the inter-stroke time duration for all flashes varied between 2 ms to 403 ms with an average of 64.318 ms. The analysis of video records and inter-stroke time duration indicated that inter-stroke times for flashes with ISCs were on average 51% longer than flashes with no ISC. Also, the CC durations for all flashes were observed to range between 1 ms to 519 ms, with an overall average of 118.45 ms, based on video records. The CC durations for flashes comprising only return strokes were on average 65% longer than flashes with ISC and return strokes.

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